# Intensity Frontier Physics: Rare Decays and Precision Measurements

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# Outline

- Physics of Intensity Frontier
- Near-Term:
  - Muon campus, Mu2e, and $g_\mu$-2
    - physics impact, feasibility, and role in world program
  - SeaQuest
    - physics goals and status
- Mid-Range:
  - Kaons and ORKA
    - potential and status
- Long-Term Project X
  - Evolution of program
    - cLFV and $g_\mu$-2
    - Kaons and Electric Dipole Moment
- Summary

# Interconnections in a Unified Program

Leptogenesis

Electroweak Baryogenesis

Neutrinos: nature, mass, impact on cosmic evolution

New Interactions:

Particles present at the dawn of the Universe

Baryon Asymmetry:

B, CP, non equilibrium

Neutrino oscillation, sterile neutrinos:

neutral LFV

Charged LFV

Muon $g_{\mu}$-2

Neutrino NSI

Kaons

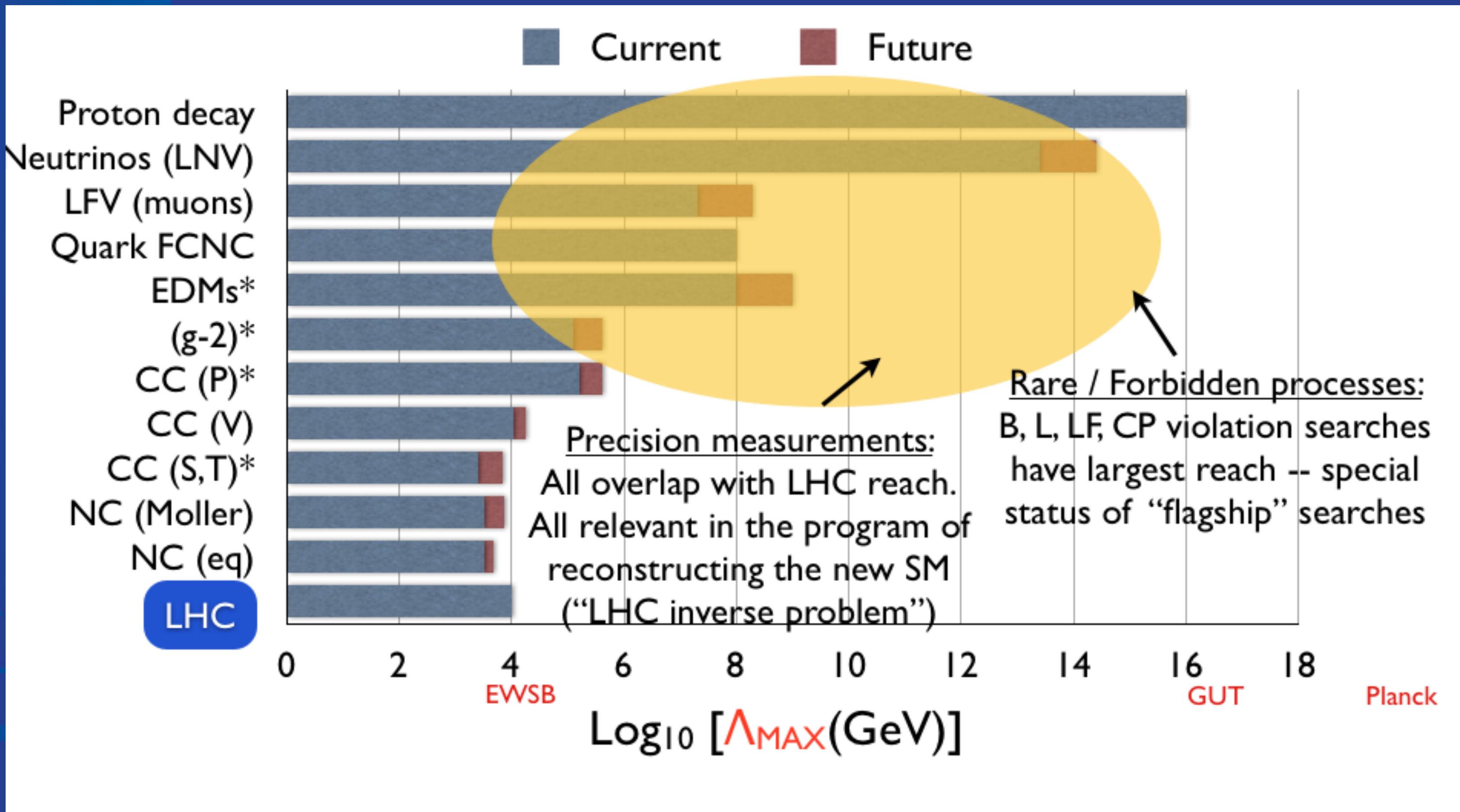
EDMs

T-violation

Kaons

After V. Cirigliano

# Physics Reach of Intensity Frontier




after V. Cirigliano

# Interrelations between Mu2e, Neutrinos, and $g_\mu$-2

- Almost all extensions of the Standard Model (SM) predict cLFV
  - the scale of new physics is ≥ 100 TeV/$c^2$ from the existing limits
- Neutrino Oscillations (*aka* neutral Lepton Flavor Violation) are linked to their charged LFV counterpart
  - models that predict cLFV are constrained and informed by oscillation measurements
- The $g_\mu$-2 anomaly is encouraging
  - flavor conserving transitions are often accompanied by flavor changing transitions at a mass scale observable by Mu2e

# Physics at the Muon Campus: A new program in this decade

# The Muon Campus Enables a Near-Term Program

- Re-purposing antiproton complex to provide world-leading muon program starting ~2016
- Will discuss physics reach and plans for
  - Mu2e
  - $g_\mu$-2
  - Later, extensions to PX
- Project Details: technical issues, cost, schedule in breakouts

# Charged Lepton Flavor Violation and Mu2e at Fermilab

# Mu2e: the first step

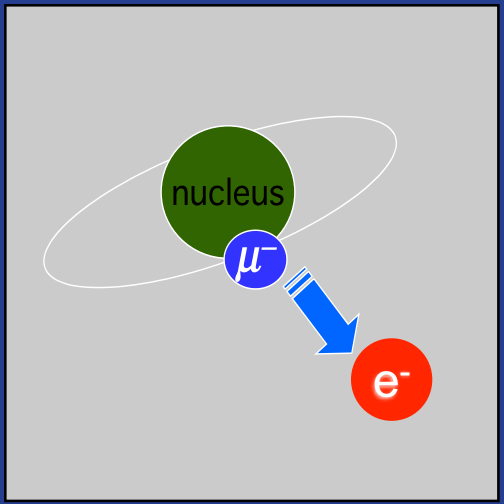
- Search for

$$R_{\mu e} = \frac{\Gamma(\mu^- N \to e^- N)}{\Gamma(\mu^- N \to \text{ all captures})} < 6 \times 10^{-17} \text{ at 90\% CL}$$

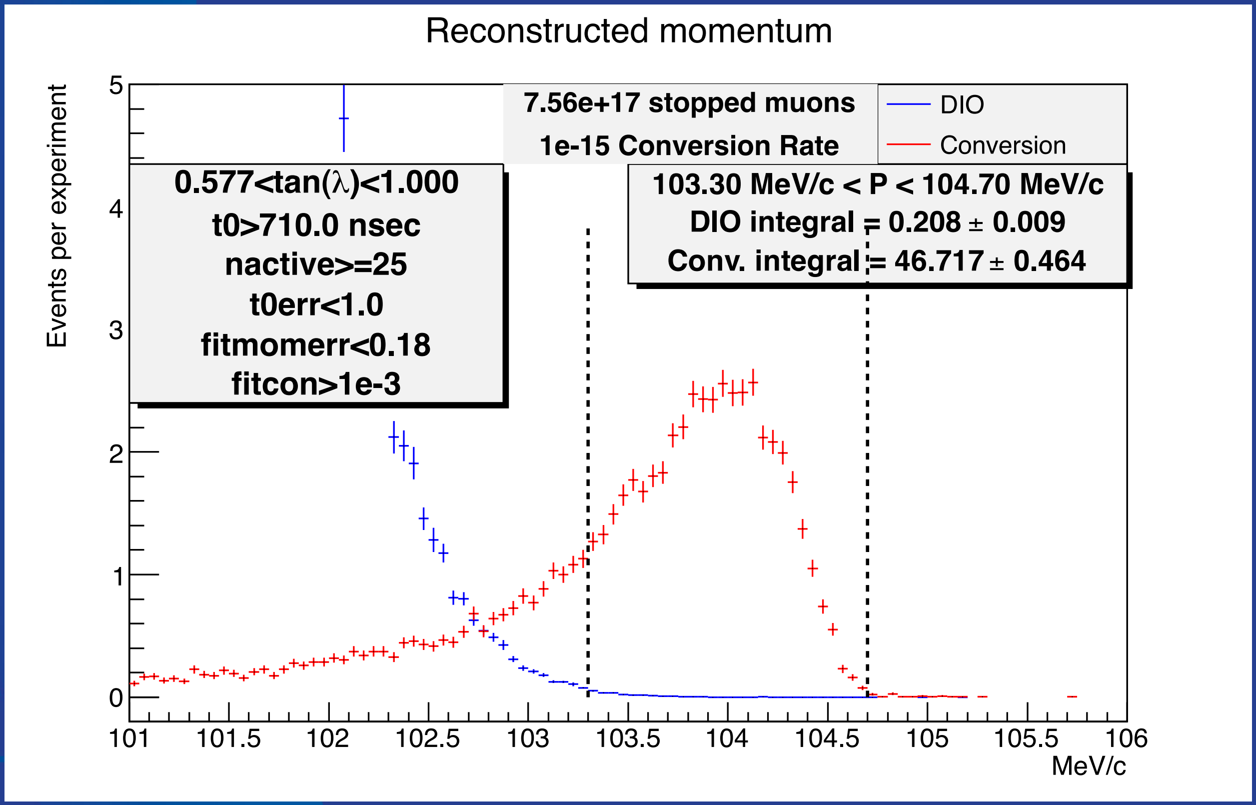
- Make an intense negative muon beam: $10^{10}$/sec
  - Hottest muon beam in the world, at FNAL Muon Campus
- Stop muons in a target and let them be captured by a nucleus
  - Signal is a monoenergetic 105 MeV electron

Al Nucleus: 4 fm

1s State: 20 fm



# Mu2e: Potential Signal



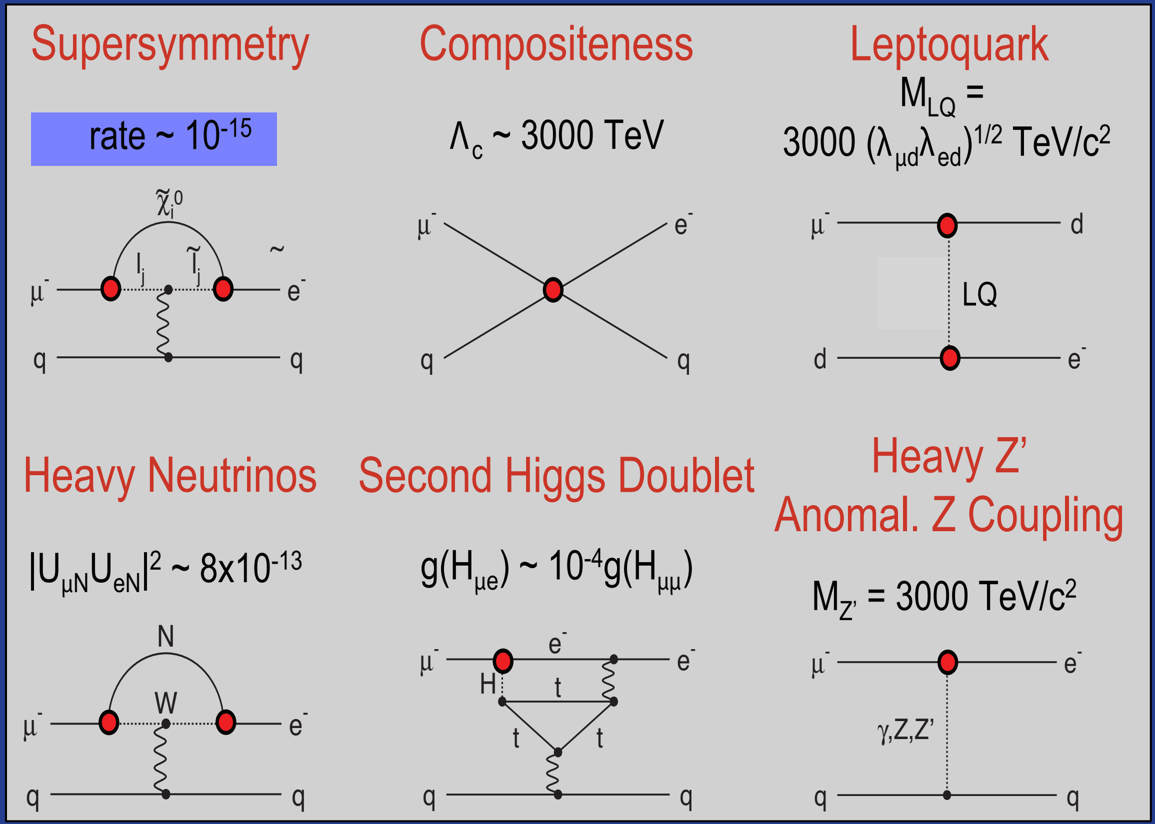

Final signal from SUSY-like rate with all cuts

~40 events in signal window

Hit-level reconstruction with accidentals and backgrounds

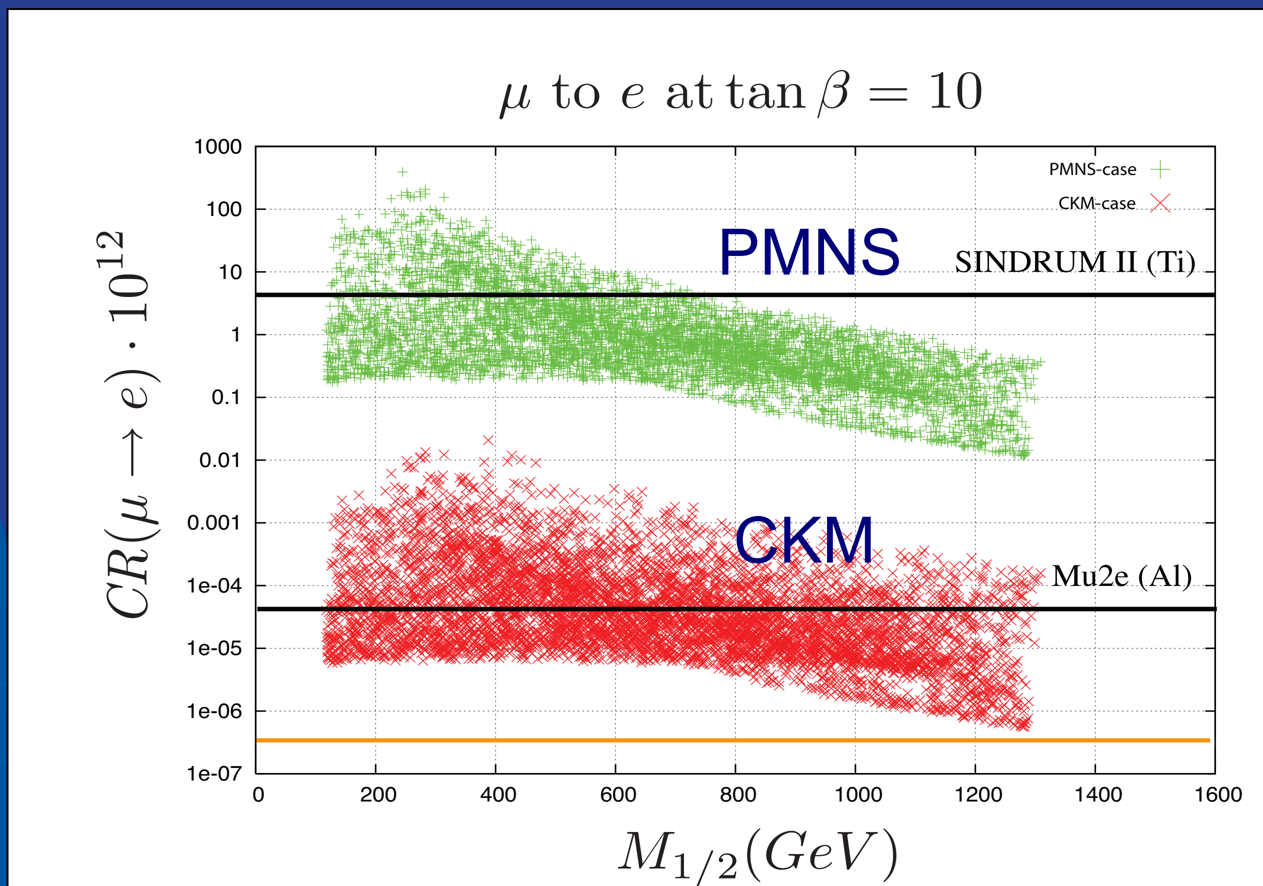
# What Physics is Explored in Mu2e?

- Mu2e will set a limit four orders-of-magnitude below current limits
- Or see a signal
- What are the physics implications?




From W. Marciano

# Mu2e has discriminating power on its own




existing measurement

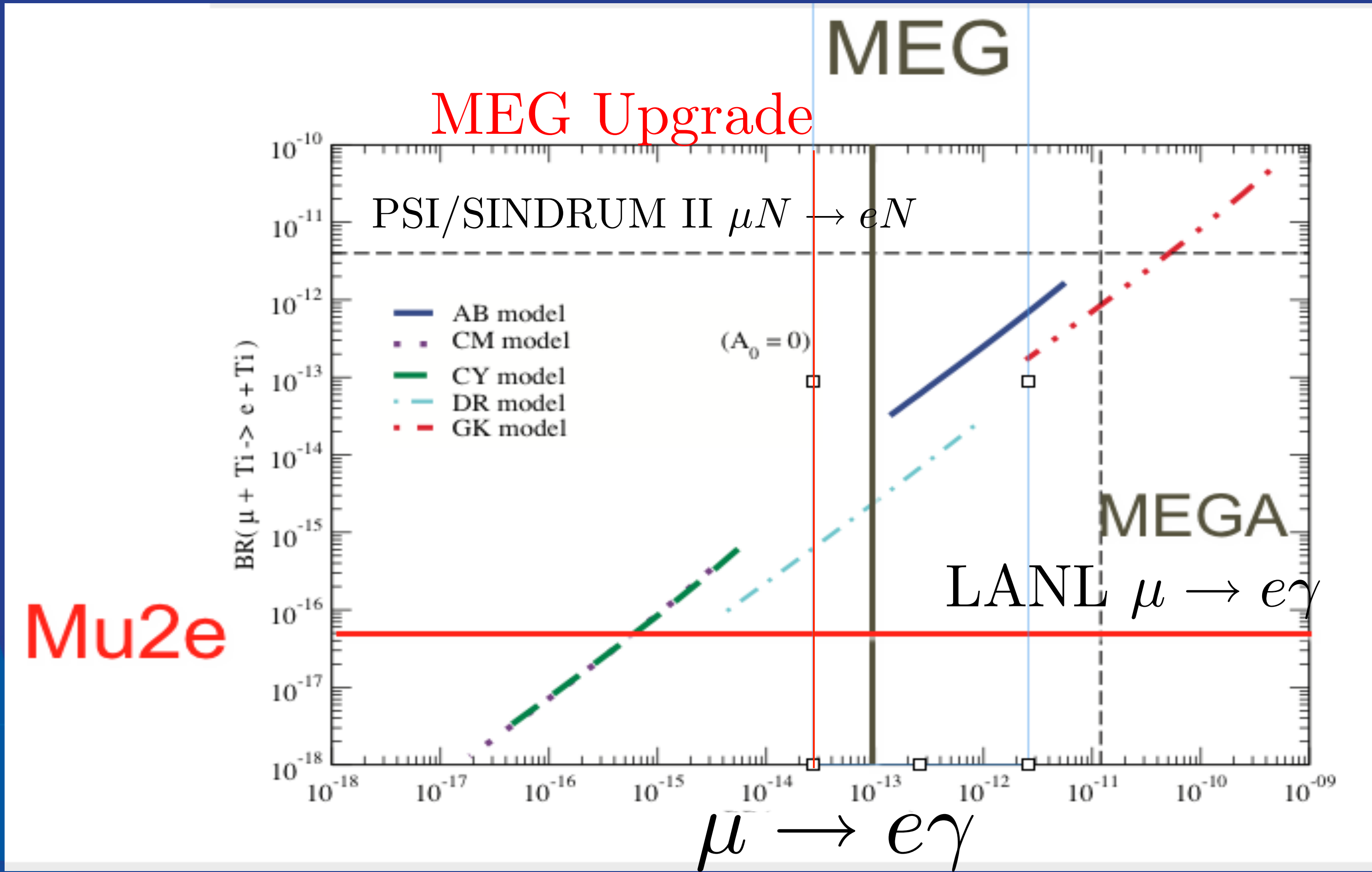
Mu2e

Mu2e At PX

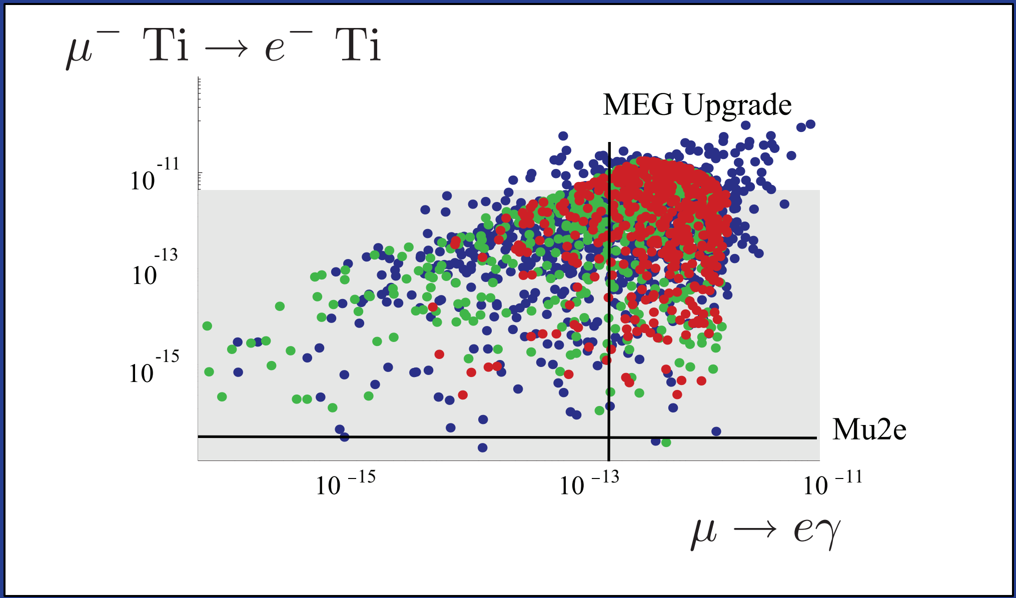
# And among models, especially when combined with other experiments

C. Albright and M. Chen, arXiv: 0802.4228, PRD D77:113010, 2008.

SO(10)



# Not just SUSY: Littlest Higgs, Randall-Sundrum, and more

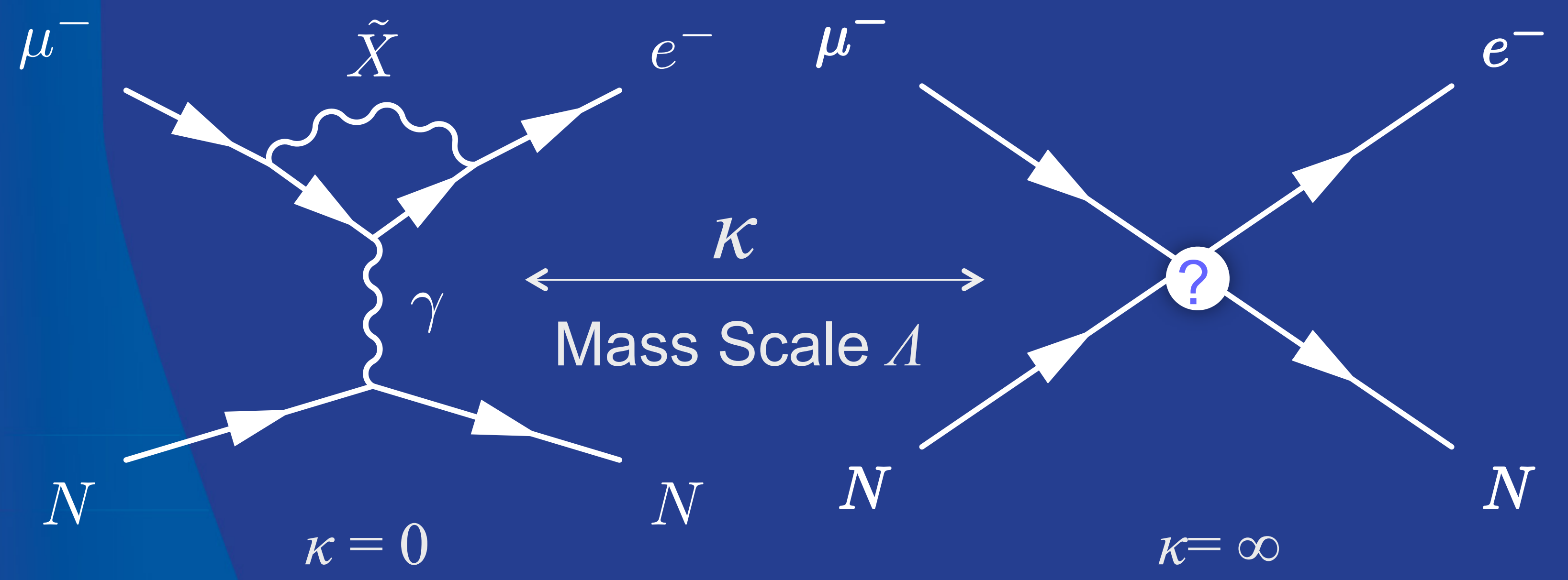



Mu2e has enormous power,
especially when combined with MEG

M. Blanke et al., **arXiv:hep-ph/0702136v3**

# “Model-Independent” Form

$$\mathcal{L}_{\mathrm{CLFV}} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_{\mathrm{L}}F^{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2}(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L)$$

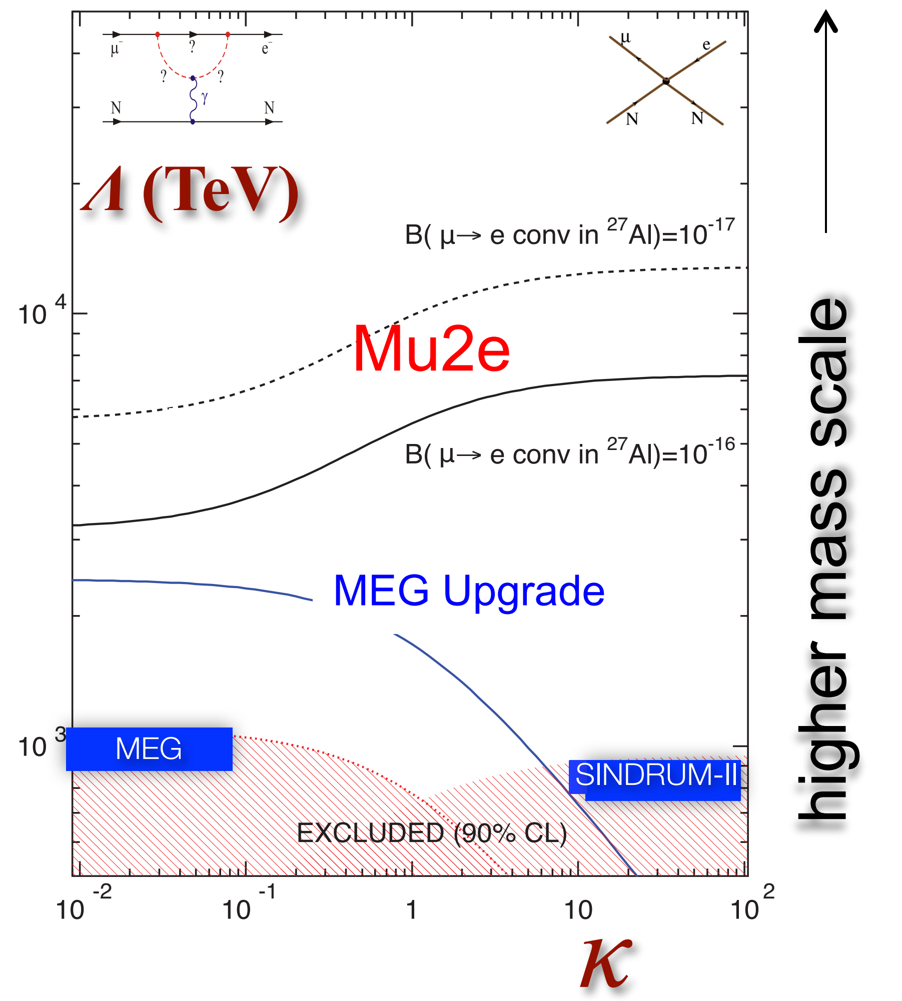



SUSY and $\mu^+ \rightarrow e\gamma$

Leptoquarks, Heavy Z,…

# Muon-Electron Conversion and $\mu^{+}\rightarrow e\gamma$

- Mu2e sees both loop and contact terms with a mass reach to ~$10^4$ TeV/$c^2$
- MEG upgrade roughly comparable on SUSY end
- Only multiple experiments can pin down theory
- 3rd Experiment in suite: $\mu^{+}\rightarrow e^{+}e^{+}e^{-}$
  - LOI at PSI



# Mu2e is "No-Lose"

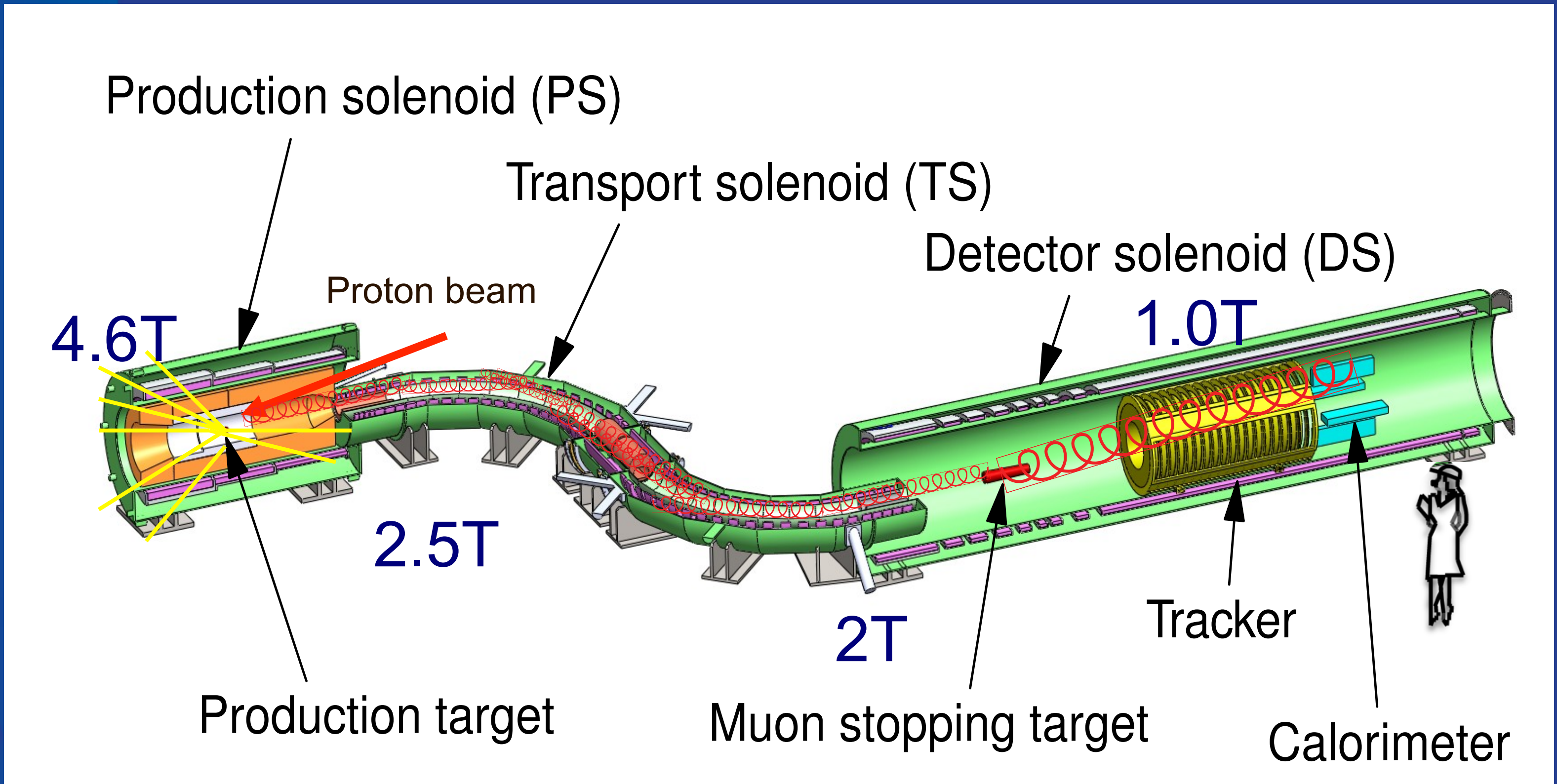
- If Mu2e sees a signal,
  it is unambiguous proof of new physics
  (SM background ~$10^{-54}$)
  - Huge discrimination power among BSM possibilities
  - Unique information and reach far beyond LHC
    - But Mu2e complements LHC discoveries or limits

- If Mu2e does not see a signal, sets severe constraints
  - Most NP models predict Mu2e should see a signal ~ 10-100 events

# Mu2e Method

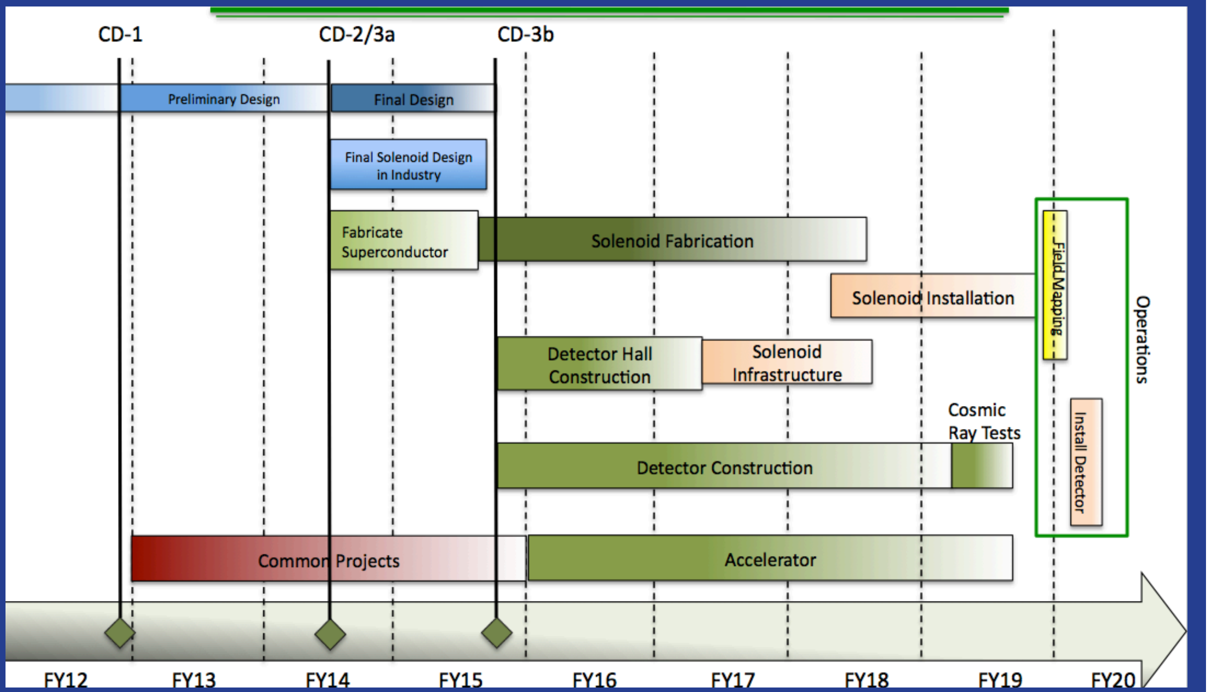
This technology is closely related to that of neutrino factories and muon colliders

- Three Superconducting Solenoids
  - Target 8 GeV protons inside first “production” solenoid
  - Transport daughter muons in S-shaped “transport” solenoid
  - Bring muons to rest in final “detector” solenoid



# Mu2e Schedule

- CD-1: 12 July 2012
- CD-2/3a next year
- Exploring ways to speed up schedule (details in breakout)
- Will start operations in early FY20

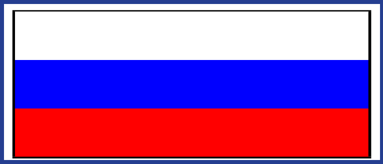


# The Mu2e Collaboration

Boston University
Brookhaven National Laboratory
University of California, Berkeley
Lawrence Berkeley National Laboratory
University of California, Irvine
California Institute of Technology
City University of New York
Duke University

Fermi National Accelerator Laboratory
Lewis University
University of Illinois, Urbana-Champaign
University of Massachusetts, Amherst Muons, Inc.
Northwestern University
Northern Illinois University
Rice University
University of Houston
University of Virginia
University of Washington

Instituto Nazionale di Fisica Nucleare Pisa
Instituto Nazionale di Fisica Nucleare, Lecce
Laboratori Nazionali di Frascati



Institute for Nuclear Research, Moscow
Joint Institute for Nuclear Research, Dubna

- 130 collaborators
- Strong INFN component

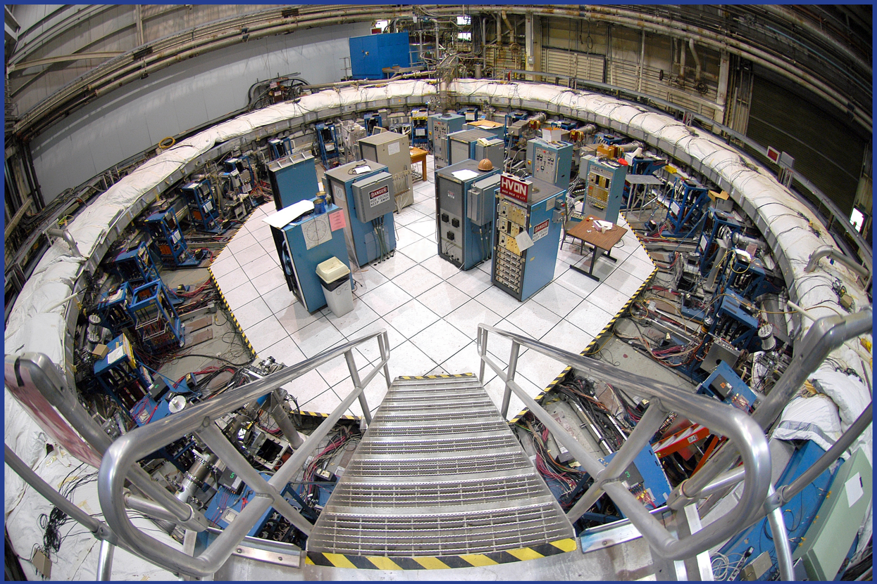
# World Context: Others Are Pursuing this Physics

- PSI:
  - $\mu^+ \rightarrow e\gamma$ : MEG is preparing an upgrade proposal
    - The upgrade is close to Mu2e on the SUSY end but still does not cover the "non-SUSY" end, giving Mu2e unique reach
  - $\mu^+ \rightarrow e^+e^+e^-$
    - LOI is submitted, proposal under development, schedule unclear
  - *Are both great experiments that could be part of PX*
- J-PARC
  - two proposed muon-electron conversion experiments at intermediate sensitivity: x10-x100 better than existing
    - DeeMe: proposed ~2015
    - COMET Phase I: ~2017
  - COMET Phase II: roughly equal to Mu2e ~2022

# Mu2e Conclusions

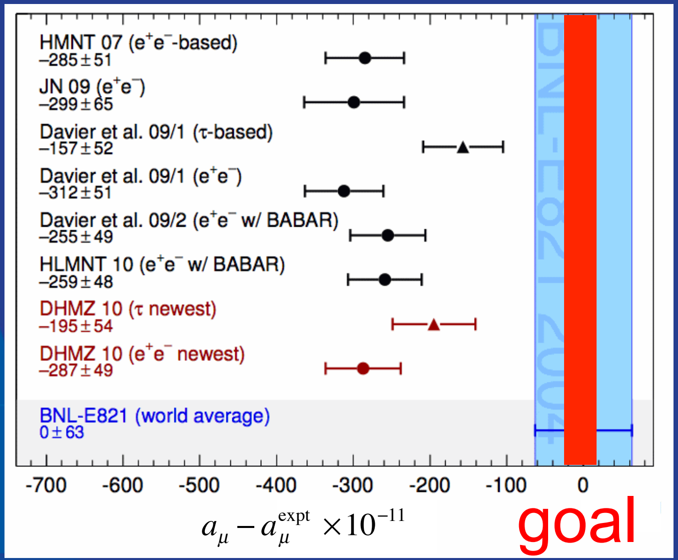
- Physics of cLFV is universally agreed to be compelling
  - Theory community, review panels endorsed it, and two other Laboratories are actively pursuing it
  - 250 papers since 2009, 74 with > 50 citations
- Mu2e will either yield either major constraints or a major discovery
  - Integral part of program with g-2 and Muon Campus
- And it leads to a cLFV program at Project X (more later)

# Muon $g_\mu$-2 at Fermilab



# $g_\mu$-2: What is Nature Trying to Tell Us?

- Many arguments about whether the anomaly is 2.9 or 3.2 or 3.6 σ
- Step Back: this is a large effect with major implications if NP




If the current discrepancy persists, reducing the exp error to 16 x $10^{-11}$ ⇒ 5.6σ discovery

Theory projected to be reduced to 30 x $10^{-11}$ over same period ⇒ 8.4σ discovery

## $g_\mu$-2: generic form

- Usual SUSY expression:

$$\Delta a_\mu \approx 130\times 10^{-11}\tan\beta\,\mathrm{sgn}\,\mu\,\left(\frac{100\ \mathrm{GeV}}{M_{\mathrm{SUSY}}}\right)^2$$

- More generally than SUSY,

$$\Delta a_\mu(\mathrm{N.P.}) = O(1)\times\left(\frac{m_\mu}{\Lambda}\right)^2\times\left(\frac{\delta m_\mu(\mathrm{N.P.})}{m_\mu}\right)$$

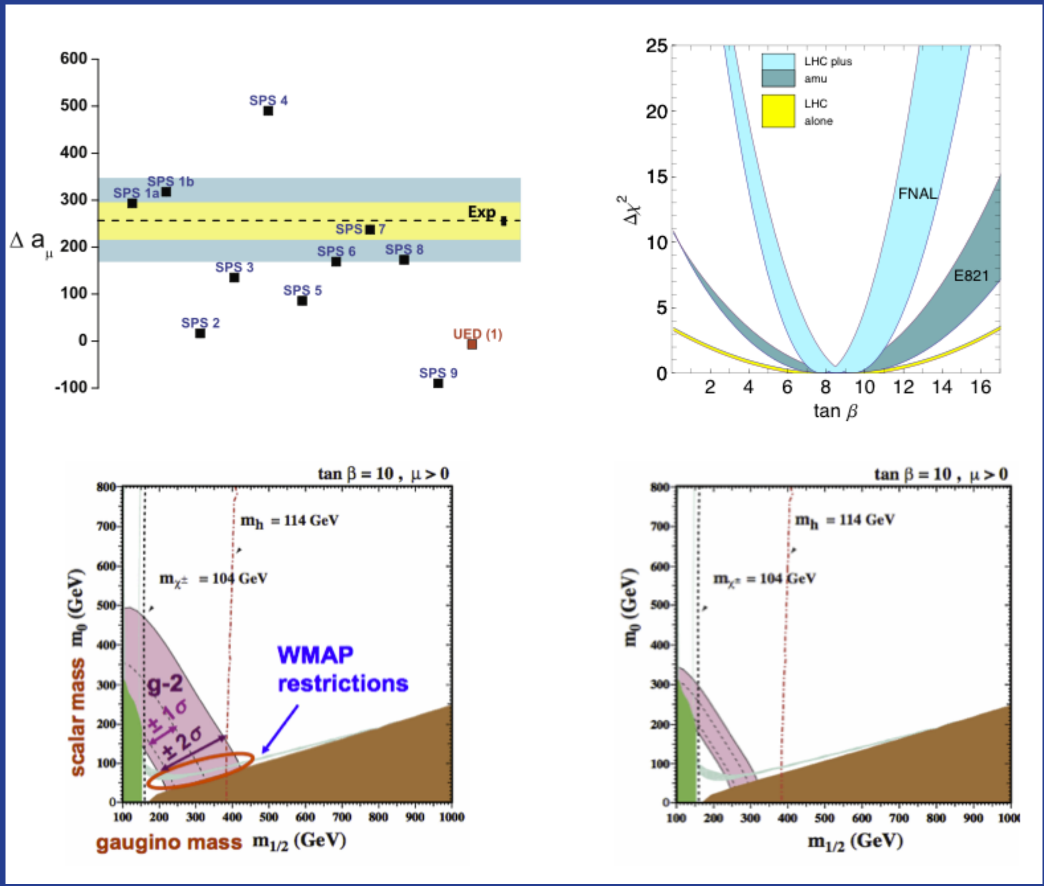
- NP terms span a wide range:
  - New weakly interacting massive particles:
    - Radiative muon mass generation: can be quite large

$$m_\mu \propto \frac{g^2}{16\pi^2}M_F$$

**A. Czarnecki and W. Marciano, Phys. Rev. D 64, 013014 (2001)**

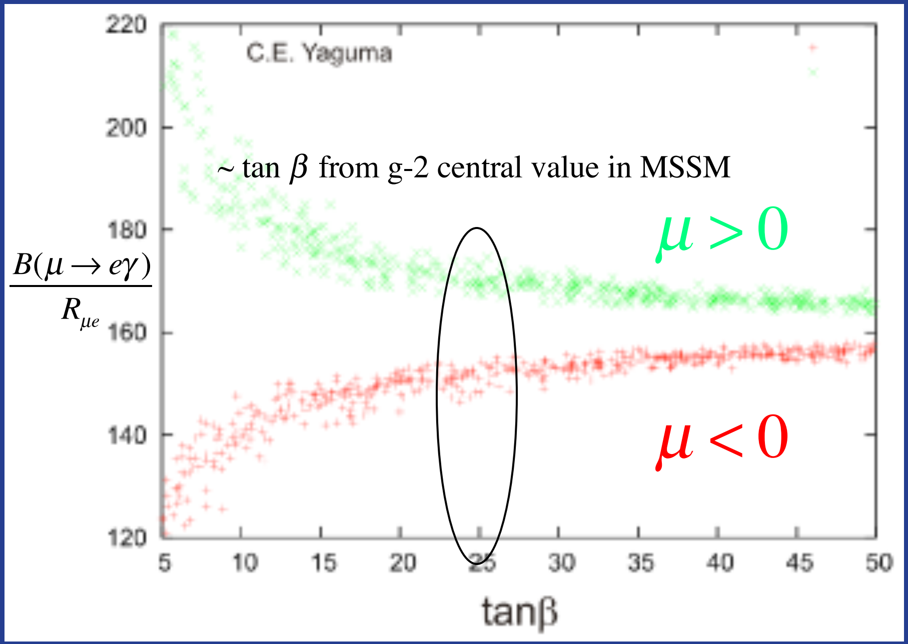
# Role of $g_\mu$-2 in the LHC Era

- New Physics (NP)at the LHC, then $g_\mu$-2 will resolve ambiguities among NP Models
- If no NP, then precision measurements such as $g_\mu$-2 are the only way to probe high energy scales



# $g_\mu$-2 makes other experiments more powerful

- Example:
  - Combined with Mu2e and $\mu \rightarrow e\gamma$



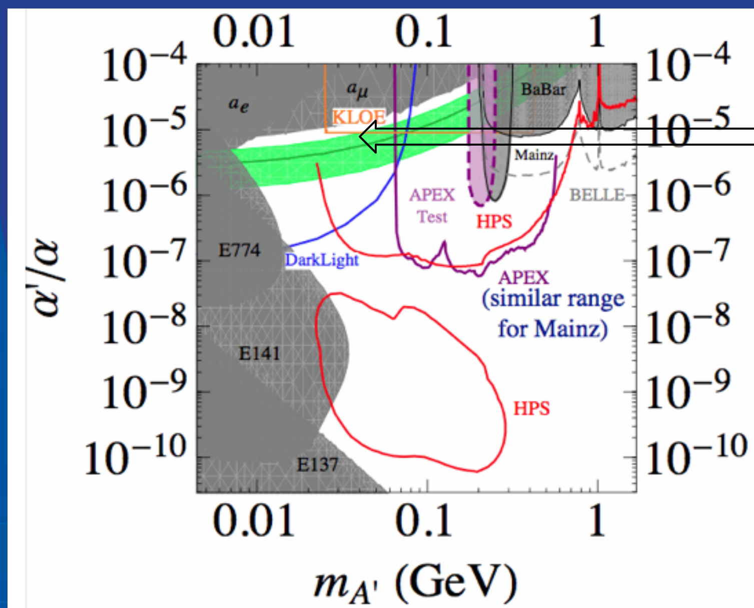

C. E. Yaguma, hep-ph/0502014v2

sgn $\mu$ is accessible

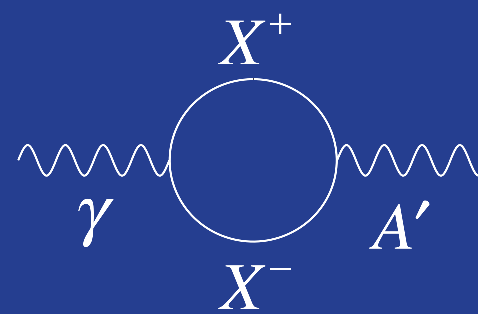
# $g_\mu$-2 and Dark Photons: Complementary to Energy Frontier

- Old idea: if there is an additional U(1) symmetry, there will be mixing between the photon and new gauge boson
  - JLab: APEX expt, DarkLight proposal

Holdom, Phys. Lett. B166, 1986




$g_\mu$-2

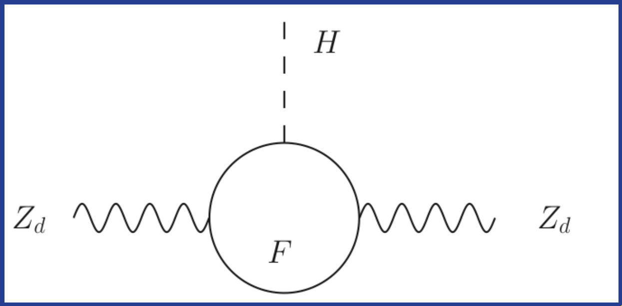



$$L = i\bar{X}\gamma^\mu(\partial_\mu - ig_D V_\mu)X - \frac{\varepsilon}{2}V^{\mu\nu}F_{\mu\nu}$$

Muon $g_\mu$-2 sensitive to new U(1) gauge force that couples dark sector to charged SM particles

# And $g_\mu$-2 may be related to Higgs Physics

- Example: explaining diphoton excess:
  - New “vector-like” fermions and gauge boson




$Z_d$ decay mimics

$H \to \gamma\gamma$

"kinetic mixing" term $\frac{\varepsilon}{2} V^{\mu\nu} F_{\mu\nu}$

  - Also the right size to explain $g_\mu$-2

  - And possible extension to Dark Matter as before

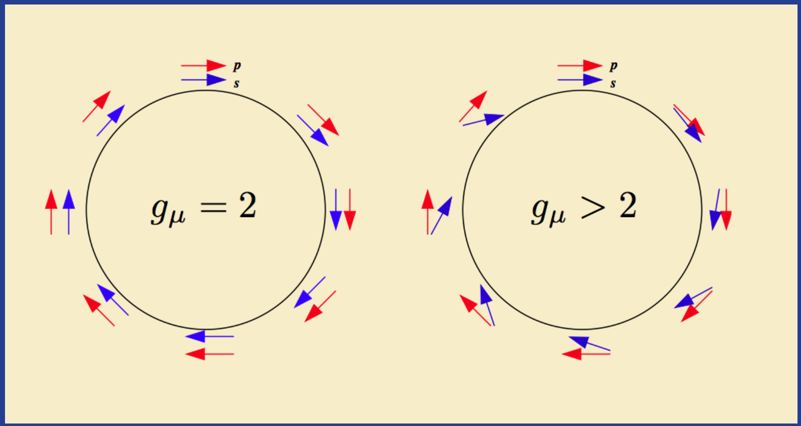
Davoudiasl, Lee and Marciano arXiv:1208.2973

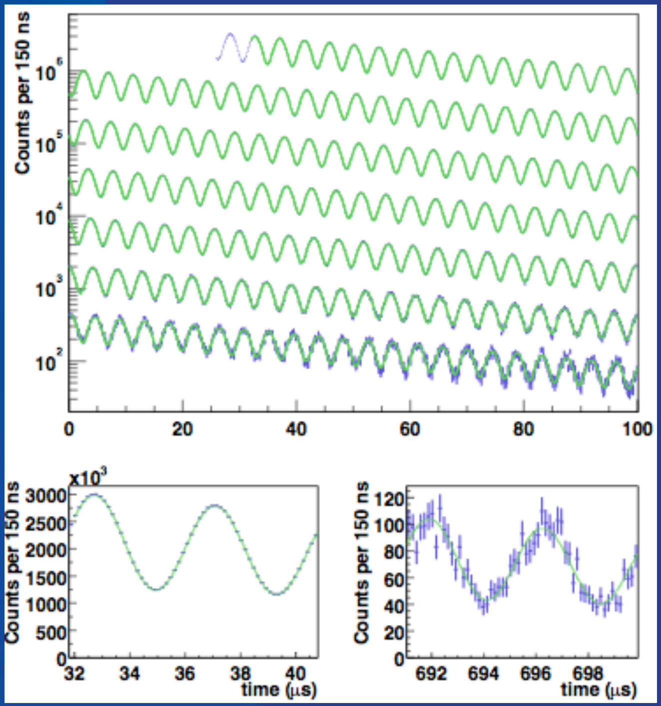
# Experimental Method of $g_\mu$-2 in a Storage Ring

$$\omega_S = g_\mu \frac{eB}{2m_\mu c} + (1-\gamma)\frac{eB}{\gamma m_\mu c}$$

$$\omega_C = \frac{eB}{\gamma m_\mu c}$$

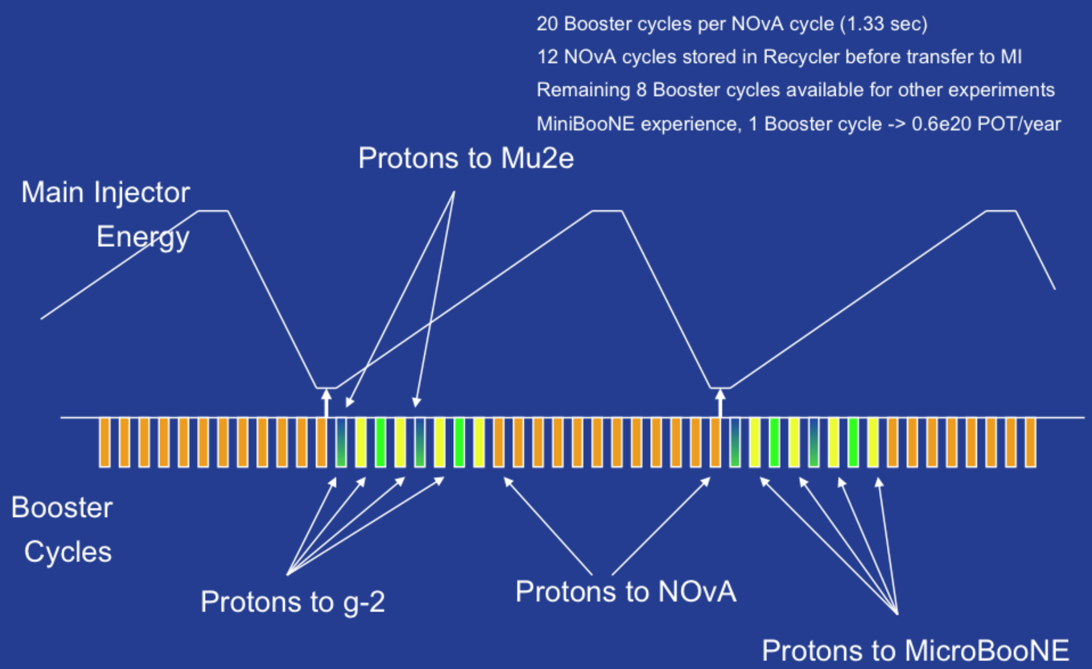
$$\omega_S - \omega_C = \frac{g_\mu - 2}{2}\frac{eB}{m_\mu c}$$



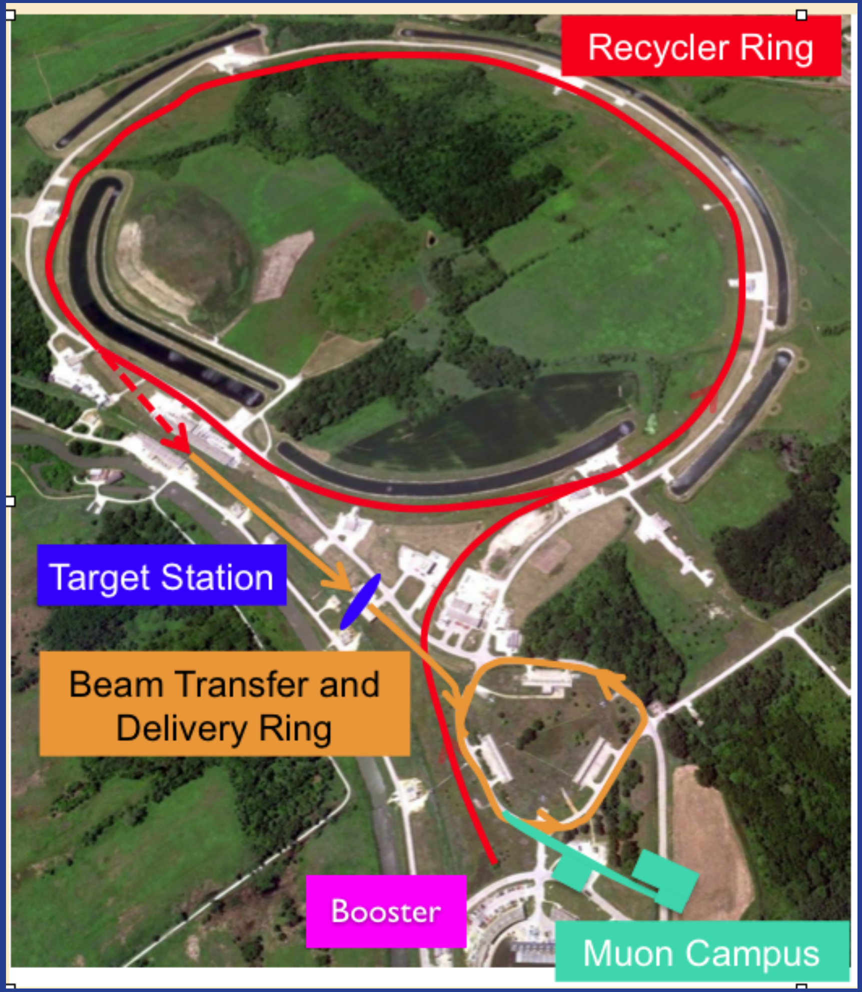

# Reduce, Reuse, Recycle: Bring to FNAL

- Made Possible by Proton Improvement Plan



# Re-use of the Complex and the new Muon Campus

- Recycler
- “Lithium Lens” that was used to make antiprotons
- And Accumulator/ Debuncher complex for Delivery to $g_\mu$-2 and Mu2e



# Partial List of Re-Used Infrastructure

## used in overall Muon Campus

- From BNL:
  - $g_\mu$-2 ring!
  - $g_\mu$-2 beamline elements
- Antiproton Complex
  - Debuncher Ring
  - Lithium Lens
  - AP transfer lines
  - AP-0 Target Station
  - AP-2/Accumulator Magnets
  - Magnets, pumps, stands and other Accumulator Ring components
- Main Injector RF ferrites
- Tevatron
  - Damper System
  - Satellite refrigerators
  - $N_2$ and He storage tanks
  - Cryogenics line
  - High Temperature Superconducting Leads
  - Shielding Steel
  - Transformers
  - Vacuum Equipment
  - Loss Monitors
  - Beam Position Monitor electronics
  - Crates
  - Control Cards
  - Miscellaneous Instrumentation

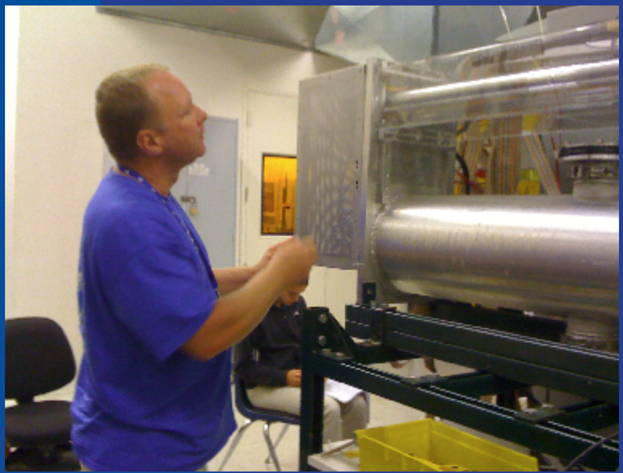
# The Storage Ring: ~$50M replacement cost

# New Technology is Used Across Experiments

- Straw Chambers in Vacuum
- Also adopted by Mu2e and CERN NA62 kaon exp't

15 μm straw wall (kapton or mylar)

Brendan Casey: Early Career Research Award



K.S. Babu et al.,Phys. Rev. D 64 (2001) 053009
J. Feng et al. ,arXiv:hep-ph/0107182v1

$$H = -\vec{\mu} \bullet \vec{B} - \vec{d} \bullet \vec{E}$$

# EDMs and $g_\mu$-2

| | E | B | $\vec{\mu}, \vec{d}$ |
|---|---|---|---|
| P | - | + | + |
| C | - | - | - |
| T | + | - | - |

$\vec{d}, \vec{J}$

parallel for intrinsic EDM

- EDMs are a unique and powerful probe into non-CKM sources of CP violation (strong CP)
- Muon EDM in the SM < $10^{-36}$: a discovery is NP
  - Most models predict linear scaling, so electron EDM provides a strong constraint: $d_e$< 1.6x $10^{-27}$ e-cm
  - But some predict quadratic or cubic scaling
- Booster $g_\mu$-2 will get a simultaneous muon EDM measurement to ~$10^{-21}$ e-cm
  - Current best limit from BNL $g_\mu$-2 of $1.8 \times 10^{-19}$

# $g_\mu$-2: World Program

- Booster experiment uses magic momentum

$$\vec{\omega}_{\alpha\eta} = -\frac{Qe}{m}\left[a_\mu \vec{B} + \left(a_\mu - \left(\frac{m}{p}\right)^2\right)\frac{\vec{\beta}\times\vec{E}}{c}\right] - \eta\frac{Qe}{2m}\left[\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right]$$

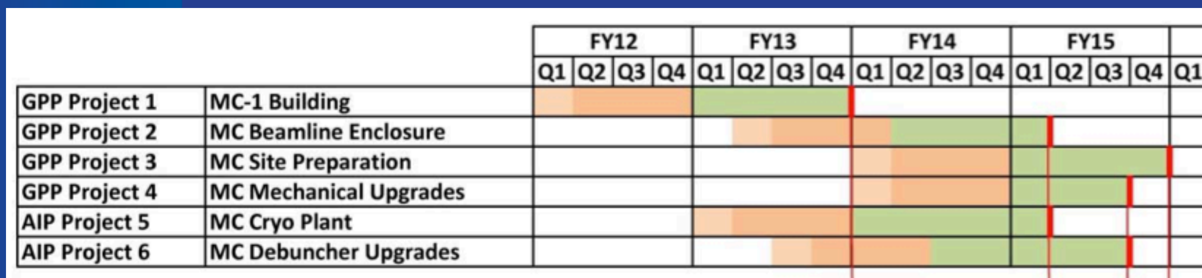
Set *p* such that this term is zero

Normally negligible

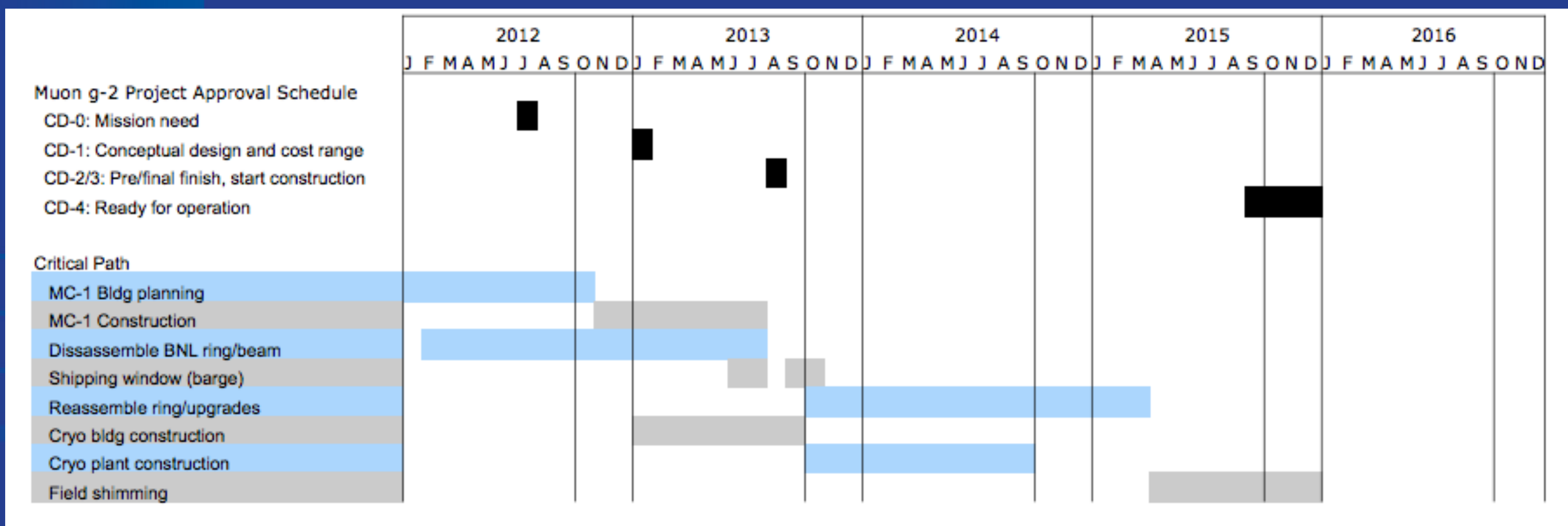
- J-PARC is interested in this physics with a very different technique still to be demonstrated

- FNAL $g_\mu$-2 has the world stage

# Muon Campus, Mu2e and $g_\mu$-2 Schedule




- Muon Campus consistent with keeping $g_\mu$-2 and Mu2e on technically-driven schedules
- $g_\mu$-2 ready for data at start of 2016



# The $g_\mu$-2 Collaboration

Argonne National Laboratory
Boston University
Brookhaven National Laboratory
Cornell University
Fermi National Accelerator Laboratory
University of Illinois, Urbana-Champaign
James Madison University
University of Kentucky
Duke University

University of Massachusetts, Amherst
University of Michigan
Muons, Inc.
Northwestern University
University of Virginia University of Washington
York College, CUNY

KEK
Instituto Nazionale di Fisica Nucleare, Lecce
Laboratori Nazionali di Frascati

~160 COLLABORATORS

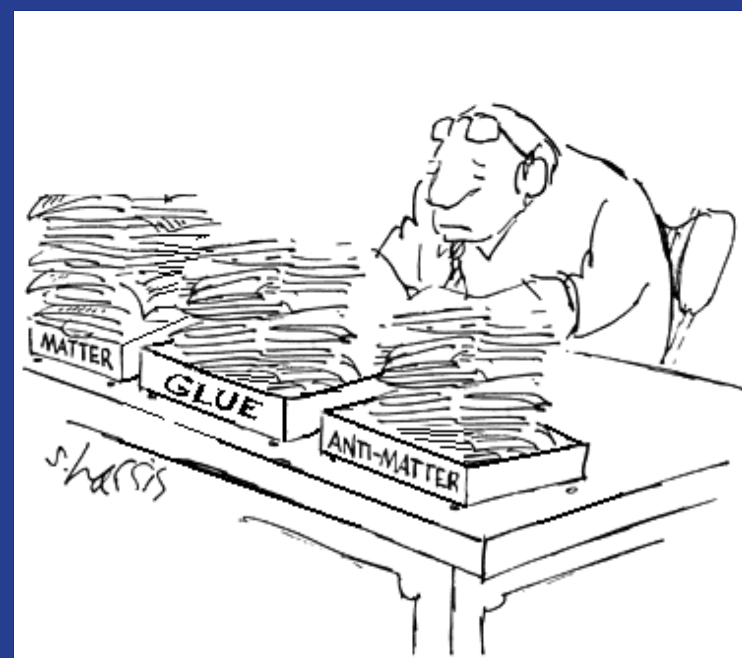
Joint Institute for Nuclear Research, Dubna
Petersburg Nuclear Physics Institute

Shanghai Jio Tong University

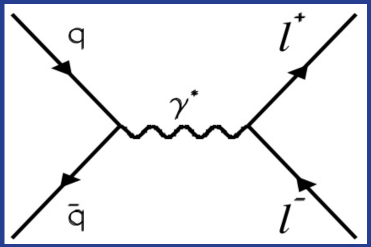
Technische Universitat Dresden

University of Groeningen, KVI

# SeaQuest: Structure of the Proton



# Physics of SeaQuest

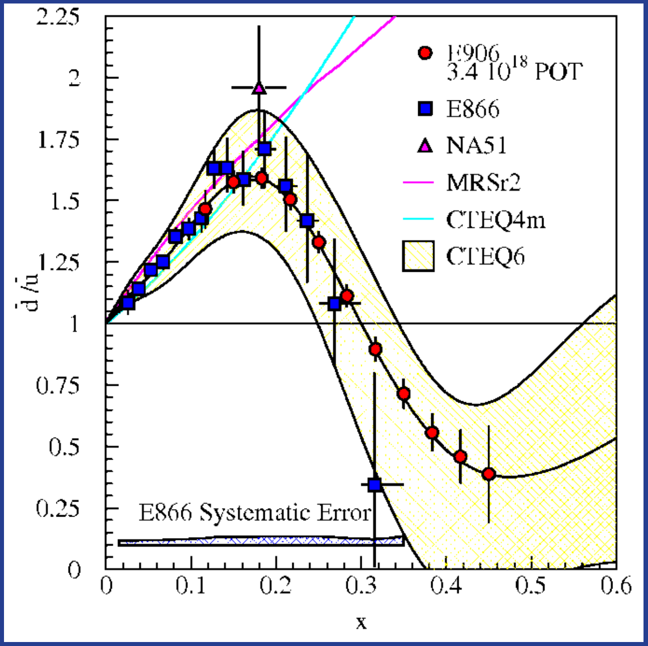



- What is the origin of the sea in the nucleon?
  - Use Drell-Yan scattering
- Do nucle*ons* change their internal properties when embedded in a nucle*us*?
  - What can the sea parton distributions tell us about the effects of nuclear binding?
  - Is confinement influenced by the nuclear medium?
- Are nuclear effects with the weak interaction the same as with the electromagnetic interaction?
  - Intermediate-x sea PDF's and $\nu$ DIS
    - Link to FNAL's MINER$\nu$A, NuTeV, …

# What is the origin of the sea in the nucleon?

- Sea asymmetries are important for understanding QCD
- What is $\bar{d}(x)/\bar{u}(x)$?

Blue previous generation;
Red expected SeaQuest Errors





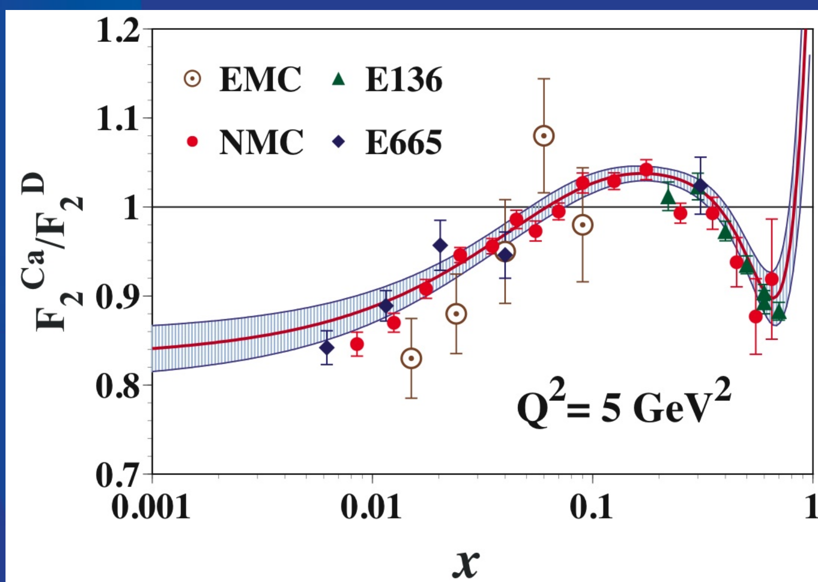



Fermilab

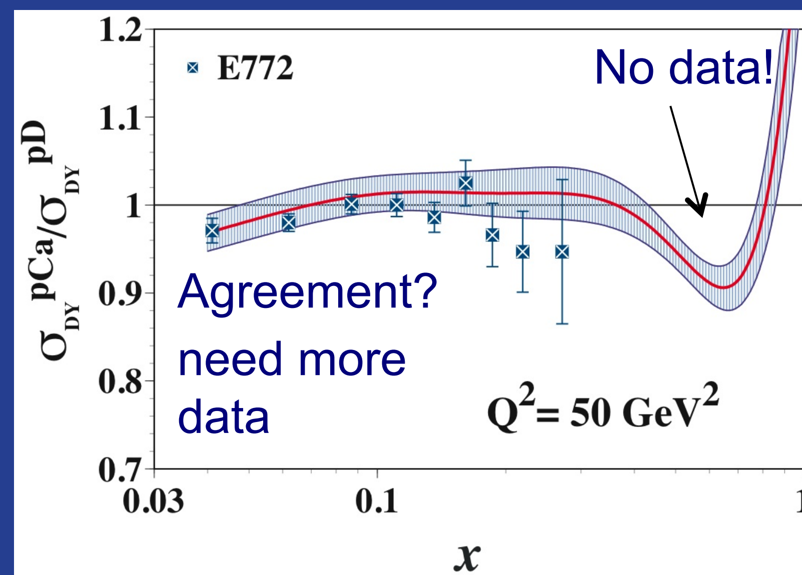
# Do nucleons change their internal properties when embedded in a nucleus?

- We've been asking this since the discovery of the EMC effect

DIS Ca/Deuterium



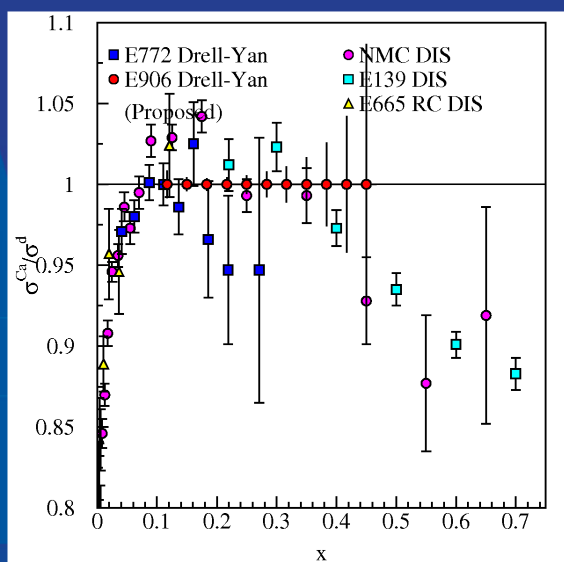

DY Ca/Deuterium



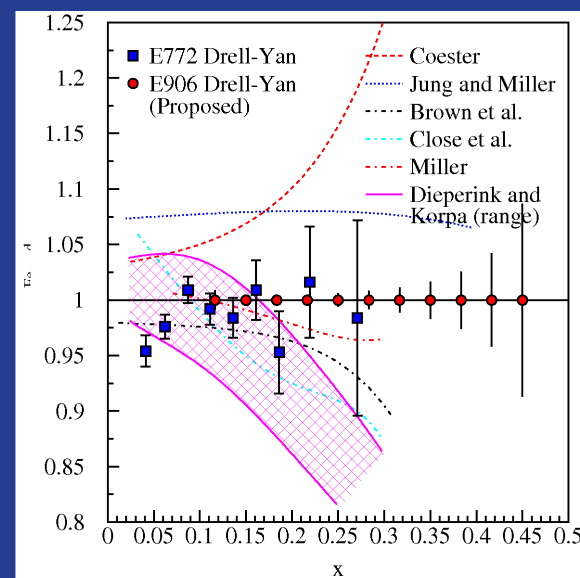
# What Will SeaQuest Add?

- Models vary widely: all was well with EMC-based model (Coester) until it clearly disagreed with Drell-Yan E772
- SeaQuest examines x < 0.45 with much smaller errors
- >2 materials enable comparisons to *ν*-DIS through MINER*ν*A

Ca/$^2$H




Fe/$^2$H





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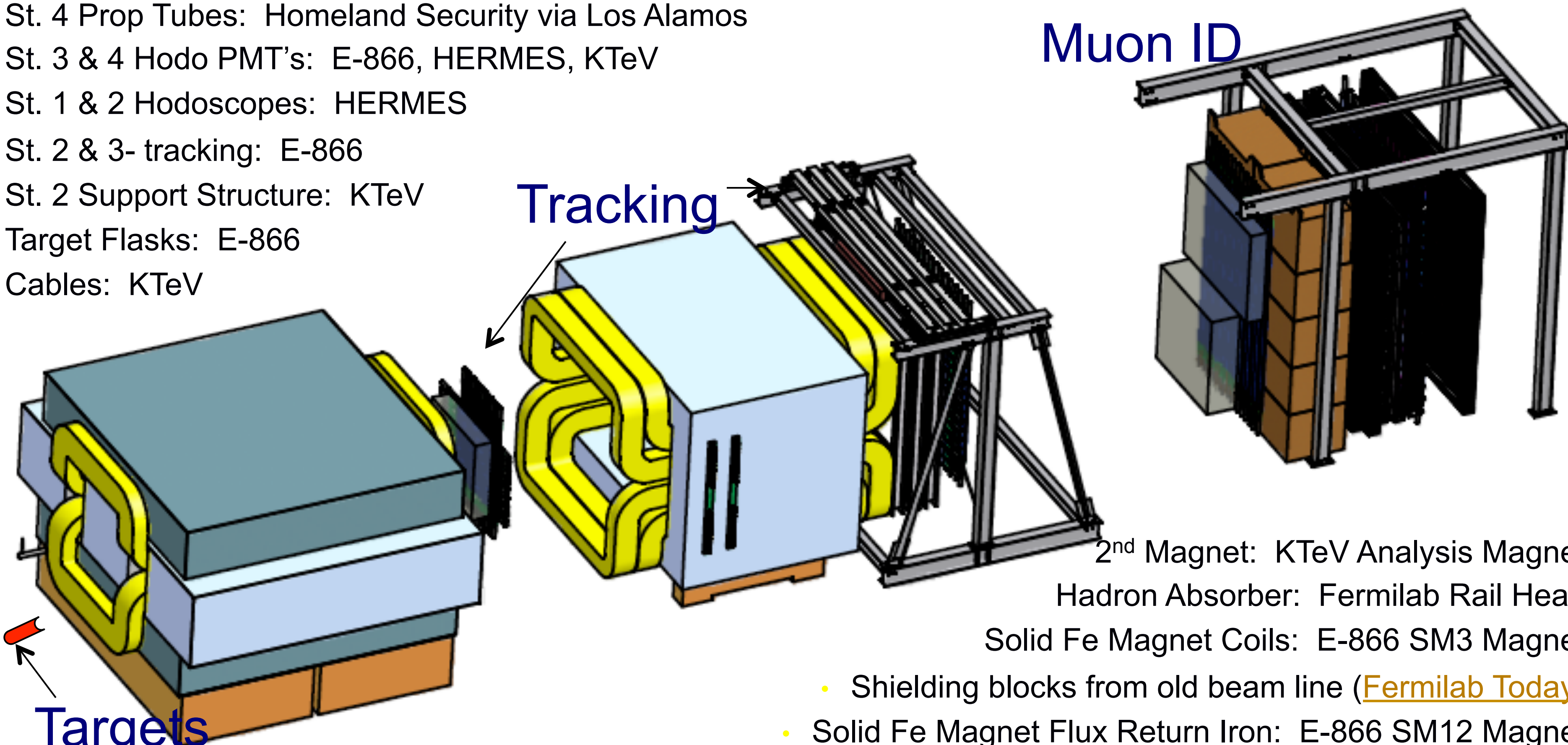
# Reduce, Reuse, Recycle:

St. 4 Prop Tubes: Homeland Security via Los Alamos
St. 3 & 4 Hodo PMT's: E-866, HERMES, KTeV
St. 1 & 2 Hodoscopes: HERMES
St. 2 & 3- tracking: E-866
St. 2 Support Structure: KTeV
Target Flasks: E-866
Cables: KTeV

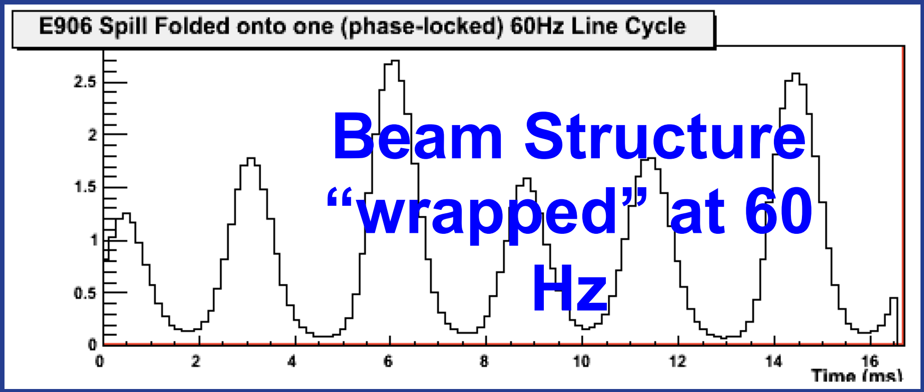


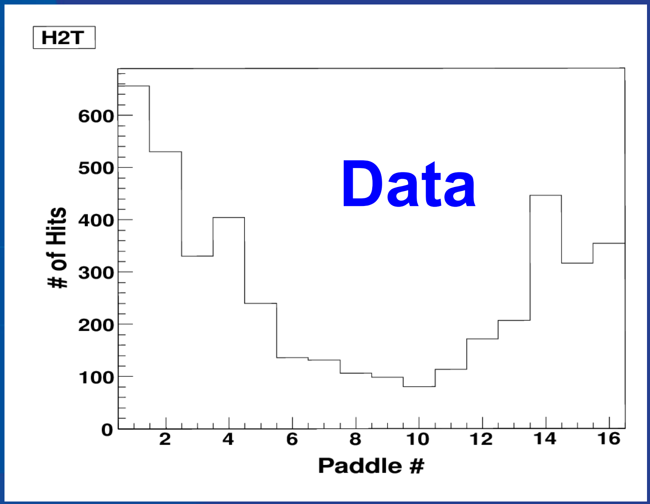

2nd Magnet: KTeV Analysis Magnet
Hadron Absorber: Fermilab Rail Head
Solid Fe Magnet Coils: E-866 SM3 Magnet

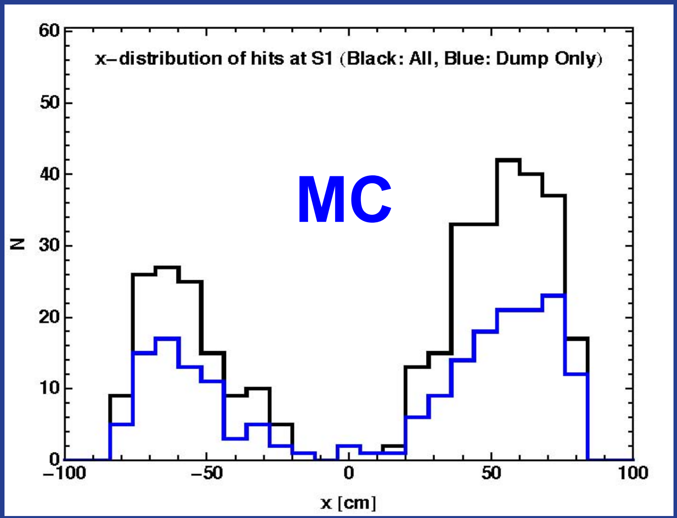
- Shielding blocks from old beam line (Fermilab Today)
- Solid Fe Magnet Flux Return Iron: E-866 SM12 Magnet

# SeaQuest Commissioning Run

- Concentrating on J/ψ physics because of short commissioning run
- Lots of good engineering data and much to do
- Will pick up post shutdown 2013-2015



# Fermilab E906/Drell-Yan Collaboration

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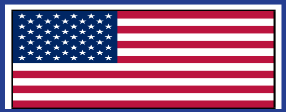
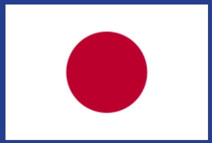


60 collaborators



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Yoshiyuki Miyachi

# Before Project X: Rare Kaon Decays and ORKA: The Golden Kaon Experiment

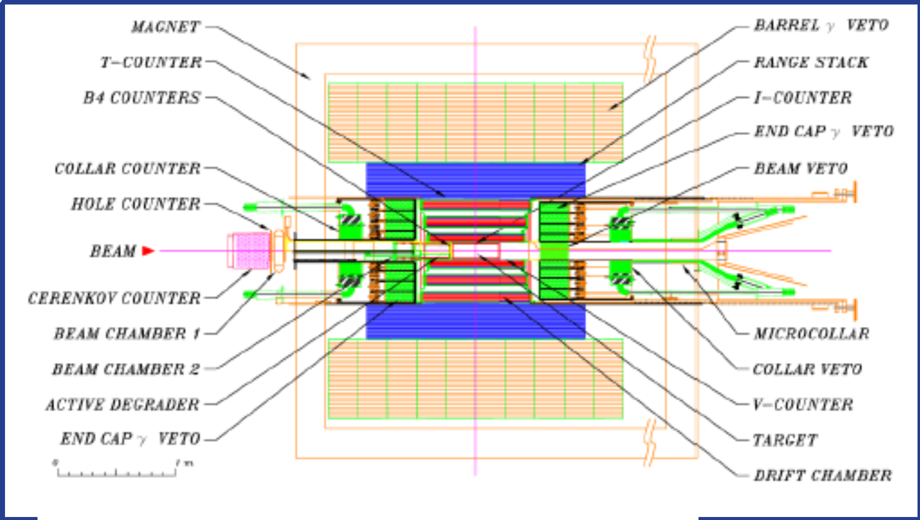
*O*bservation of rare *KA*on *A*mplitudes, *aka* Orcinus orca

# ORKA at the Main Injector

- 4th Generation $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ experiment
- Incremental Improvements
  - 600 MeV/c
  - K stopping rate x5 with comparable instantaneous rate
  - Larger solid angle
  - Acceptance x 10
  - Fine segmentation, improved resolutions
- Reduced Backgrounds

*Overall, >100 x sensitivity*

1000 events vs. current 7

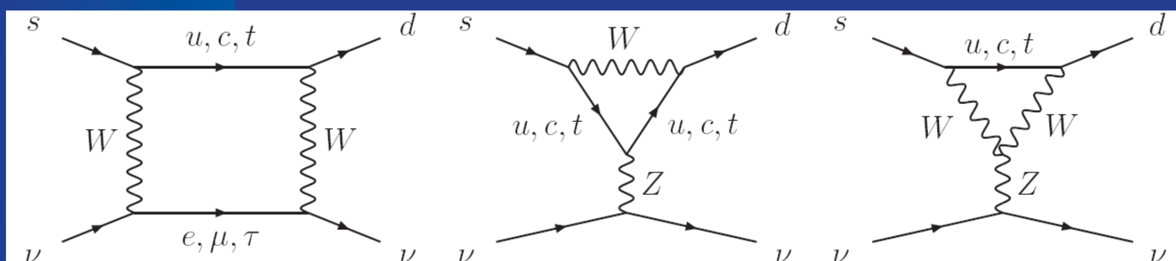


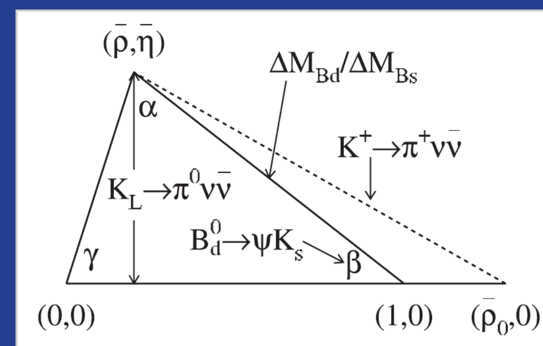

| Component | Acceptance factor |
|---|---|
| $\pi \rightarrow \mu \rightarrow e$ | $2.24 \pm 0.07$ |
| Deadtimeless DAQ | 1.35 |
| Larger solid angle | 1.38 |
| 1.25-T B field | $1.12 \pm 0.05$ |
| Range stack segmentation | $1.12 \pm 0.06$ |
| Photon veto | $1.65^{+0.39}_{-0.18}$ |
| Improved target | $1.06 \pm 0.06$ |
| Macro-efficiency | $1.11 \pm 0.07$ |
| Delayed coincidence | $1.11 \pm 0.05$ |
| Product ($R_{acc}$) | $11.28^{+3.25}_{-2.22}$ |

Can estimate errors on acceptances from experience

# $K^+ \to \pi^+ \nu\bar{\nu}$ in the Standard Model

- One of the few precisely predicted FCNC decays with quarks: $B_{SM}(K^+ \to \pi^+\nu\bar{\nu}) = (7.8 \pm 0.8) \text{ x } 10^{-11}$




- A single effective operator $\left(\bar{s}_L\gamma^\mu d_L\right)\left(\bar{\nu}_L\gamma_\mu\upsilon_L\right)$
  - Dominated by top quark (charm significant, but controlled)
  - Hadronic matrix element shared with Ke3



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# With enormous physics reach

- Aside from flagship mode:

| Process | Current | ORKA | Comment |
|---|---|---|---|
| $K^+ \to \pi^+ \nu\bar{\nu}$ | 7 events | 1000 events | |
| $K^+ \to \pi^+ X^0$ | $< 0.73 \times 10^{-10}$ @ 90% CL | $< 2 \times 10^{-12}$ | $K^+ \to \pi^+ \nu\bar{\nu}$ is a background |
| $K^+ \to \pi^+ \pi^0 \nu\bar{\nu}$ | $< 4.3 \times 10^{-5}$ | $< 4 \times 10^{-8}$ | |
| $K^+ \to \pi^+ \pi^0 X^0$ | $<\sim 4 \times 10^{-5}$ | $< 4 \times 10^{-8}$ | |
| $K^+ \to \pi^+ \gamma$ | $< 2.3 \times 10^{-9}$ | $< 6.4 \times 10^{-12}$ | |
| $K^+ \to \mu^+ \nu_{heavy}$ | $< 2 \times 10^{-8} - 1 \times 10^{-7}$ | $< 1 \times 10^{-10}$ | 150 MeV $< m_\nu <$ 270 MeV |
| $K^+ \to \mu^+ \nu_\mu \nu\bar{\nu}$ | $< 6 \times 10^{-6}$ | $< 6 \times 10^{-7}$ | |
| $K^+ \to \pi^+ \gamma\gamma$ | 293 events | 200,000 events | |
| $\Gamma(Ke2)/\Gamma(K\mu 2)$ | $\pm 0.5\%$ | $\pm 0.1\%$ | |
| $\pi^0 \to \nu\bar{\nu}$ | $< 2.7 \times 10^{-7}$ | $< 5 \times 10^{-8}$ to $< 4 \times 10^{-9}$ | depending on tech nique |
| $\pi^0 \to \gamma X^0$ | $< 5 \times 10^{-4}$ | $< 2 \times 10^{-5}$ | |

# ORKA Status

- Would use CDF Solenoid and Main Injector
  - Slow spill from MI using experience from SeaQuest
- The Lab is ensuring ORKA remains possible
  - Stage 1 Approval
  - Lab ensuring ORKA could re-use CDF Solenoid
  - Collaboration Growing
  - Refining and validating cost estimate
    - Funding needs to be understood

# World Program: NA62 and J-PARC

$$K^+ \to \pi^+ \nu\bar{\nu}$$

$Now:\ \ \mathrm{B}(K^+ \to \pi^+ \nu\bar{\nu}) = 1.73^{+1.15}_{-1.05} x10^{-10}$

(7 events)

*Future*: Sensitivity at SM $7.8\ x10^{-11}$

| Goal | NA62* | ORKA | Proj X |
|---|---|---|---|
| Events/yr | 40 | 200 | 340 |
| S/N | 10 | 5 | 5 |
| Precision | 10% | 5% | 3% |

*O(100) events, S/B≈10; physics runs: 2014-15, commissioning run with partial detector in 2012
P. Cenci, PX Workshop

$$K^0_L \to \pi^0 \nu\bar{\nu}$$

$Now:\ \ \mathrm{B}(K^0_L \to \pi^0 \nu\bar{\nu}) < 2.6\,x10^{-8}$

$Future:\ \ $ Sensitivity at SM $2.4\,x10^{-11}$

| Goal | KOTO* | ORKA |
|---|---|---|
| Events/yr | ~1 | "200" |
| S/N | ~1 | 5–10 |
| Precision | | 5% |

*starting beam power low by x50 but being worked on
J-PARC plans a phase II to reach higher sensitivity

# Project X and the Intensity Frontier

Stages matched to development of experiments

| Program: | Onset of NOvA operations in 2013 | Stage-1: 1 GeV CW Linac driving Booster & Muon, n/edm | Stage-2: Upgrade to 3 GeV CW Linac | Stage-3: Project X RDR | Stage-4: Beyond RDR: 8 GeV power upgrade to 4MW |
|---|---|---|---|---|---|
| MI neutrinos | 470-700 kW** | 515-1200 kW** | 1200 kW | 2450 kW | 2450-4000 kW |
| 8 GeV Neutrinos | 15 kW +0-50kW** | 0-42 kW* + 0-90 kW** | 0-84 kW* | 0-172 kW* | 3000 kW |
| 8 GeV Muon program e.g, (g-2), Mu2e-1 | 20 kW | 0-20 kW* | 0-20 kW* | 0-172 kW* | 1000 kW |
| 1-3 GeV Muon program, e.g. Mu2e-2 | ----- | 80 kW | 1000 kW | 1000 kW | 1000 kW |
| Kaon Program | 0-30 kW** (<30% df from MI) | 0-75 kW** (<45% df from MI) | 1100 kW | 1870 kW | 1870 kW |
| Nuclear edm ISOL program | none | 0-900 kW | 0-900 kW | 0-1000 kW | 0-1000 kW |
| Ultra-cold neutron program | none | 0-900 kW | 0-900 kW | 0-1000 kW | 0-1000 kW |
| Nuclear technology applications | none | 0-900 kW | 0-900 kW | 0-1000 kW | 0-1000 kW |
| # Programs: | 4 | 8 | 8 | 8 | 8 |
| Total max power: | 735 kW | 2222 kW | 4284 kW | 6492 kW | 11870kW |

# Evolution of Fermilab Program at Project X

| | Project X |
|---|---|
| • Neutrino oscillation, sterile neutrinos | • **Grows to full-scale LBNE with staged development** |
| • Charged LFV, Muon $g_\mu$-2, Kaons, Neutrino NSI | • **X100 in current muon program and enables world-*leading* program in muon cLFV and kaons – multiple channels** |
| • EDMs and T-Violation | • **Requires Project X** |

# Muon Physics at Project X

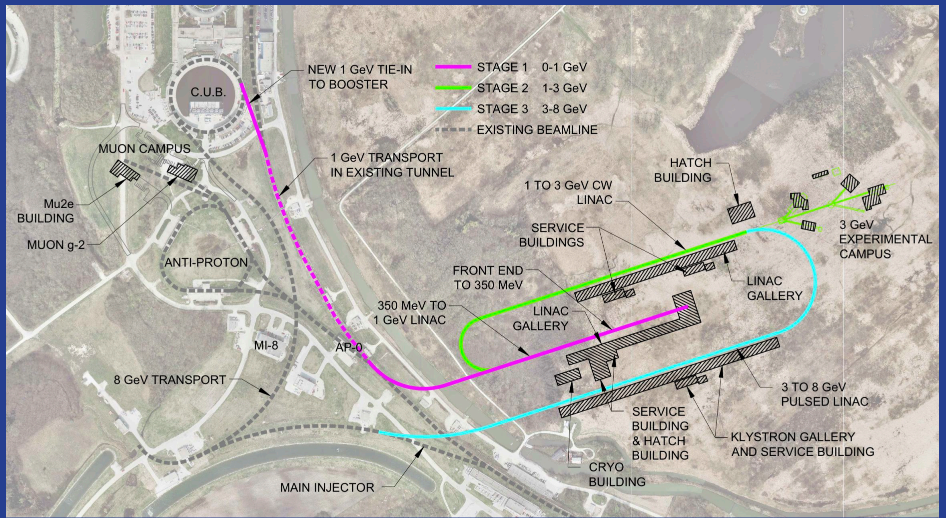
Who ordered that?

Still a good question after > 70 years

# g-2, Mu2e, and the Muon Campus at Project X

- Each stage of Project X will advance the physics reach of the complex

- This is just one possible evolution that follows Project X staging
  - Stage 1: 1 GeV (x10 improvement)
    - Either continue running or reconfigure Mu2e
  - Stage 2: 1–3 GeV (x100 improvement)
    - optimum for Mu2e?
  - Stage 3: 3–8 GeV
    - Muons in more modes, next generation $g_{\mu}$-2 and EDM




one possibility





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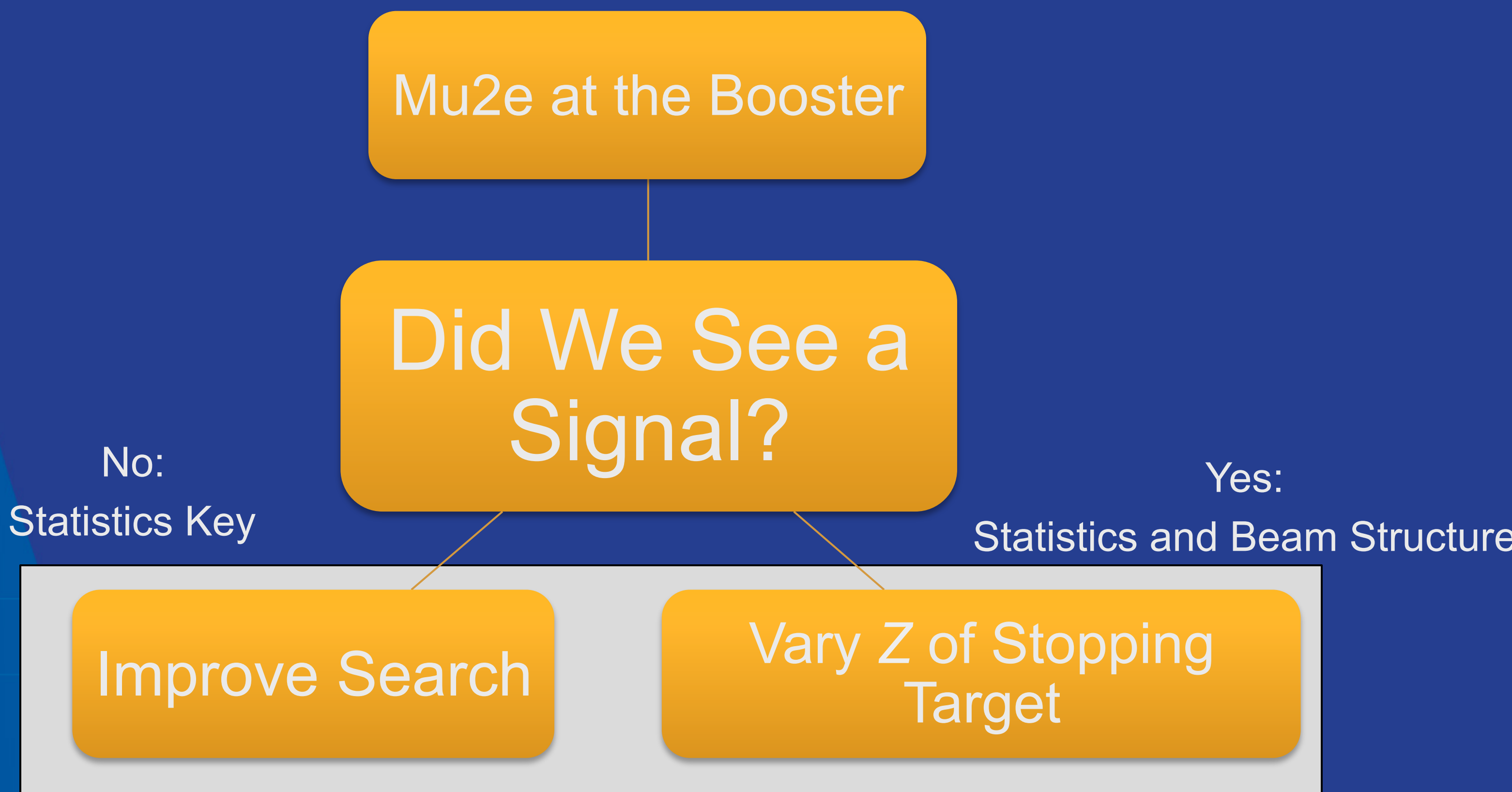
# Next Step in cLFV Program: Requires Project X



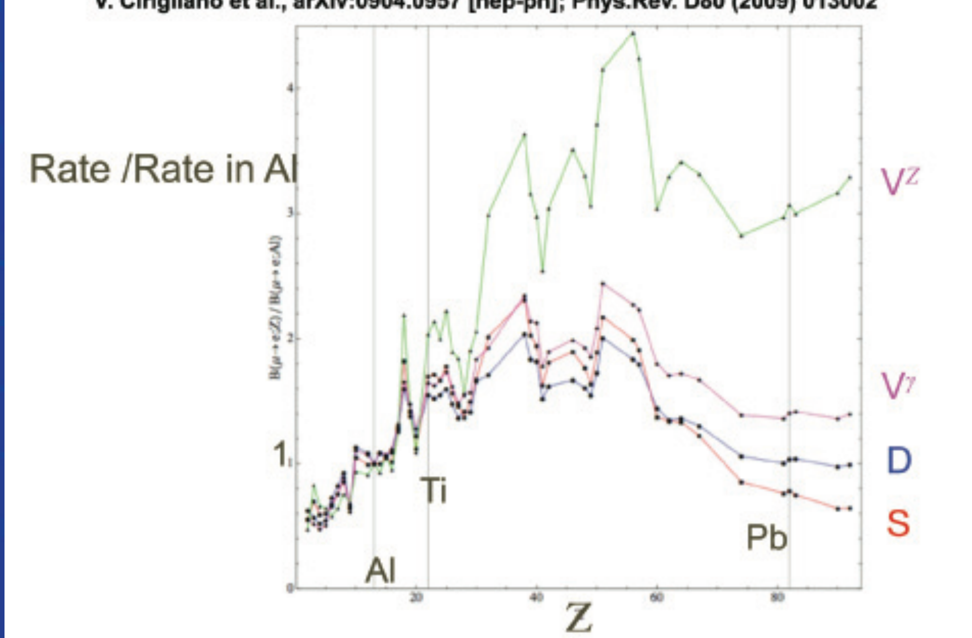
# Case I: No Signal, Improve Search

- The FNAL Booster/Existing Muon Campus will limit statistical power: $10^{10}$ muons/sec
  - About x10 limit on intensity from existing complex: shielding, RF, etc. This is why Mu2e traded intensity for running time to save money: now three years instead of originally proposed one year.
- Project X can yield $10^{13}$ muons/sec
  - 3 GeV KE protons about optimal, nicely matched to PX.
    - otherwise we may hit a systematic limit from backgrounds arising from antiproton production.
    - Use of 1 GeV protons and recycling Mu2e study underway
- Detector and Beam Improvements needed if Mu2e continues at the Booster
  - not to say easy or well-thought-out but not qualitatively new

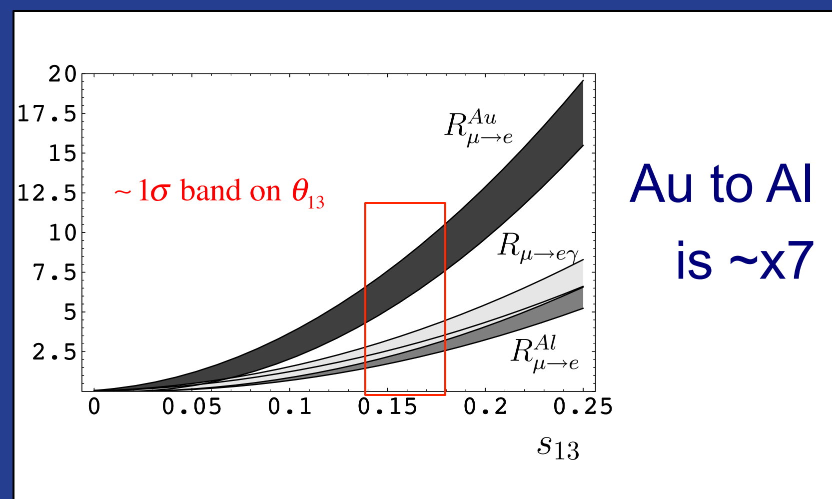
# Case II: Study a Signal

- Vary *Z* of target to study new physics
- Explicit link to neutrinos through $\theta_{13}$

V. Cirigliano et al., arXiv:0904.0957 [hep-ph]; Phys.Rev. D80 (2009) 013002




$\theta_{13}$: G. Fogli et al., arXiv:1205.5254




V. Cirigliano, B. Grinstein, G. Isidori, M. Wise
**Nucl.Phys.B728:121-134,2005**

# Signal: Absolutely Requires Project X

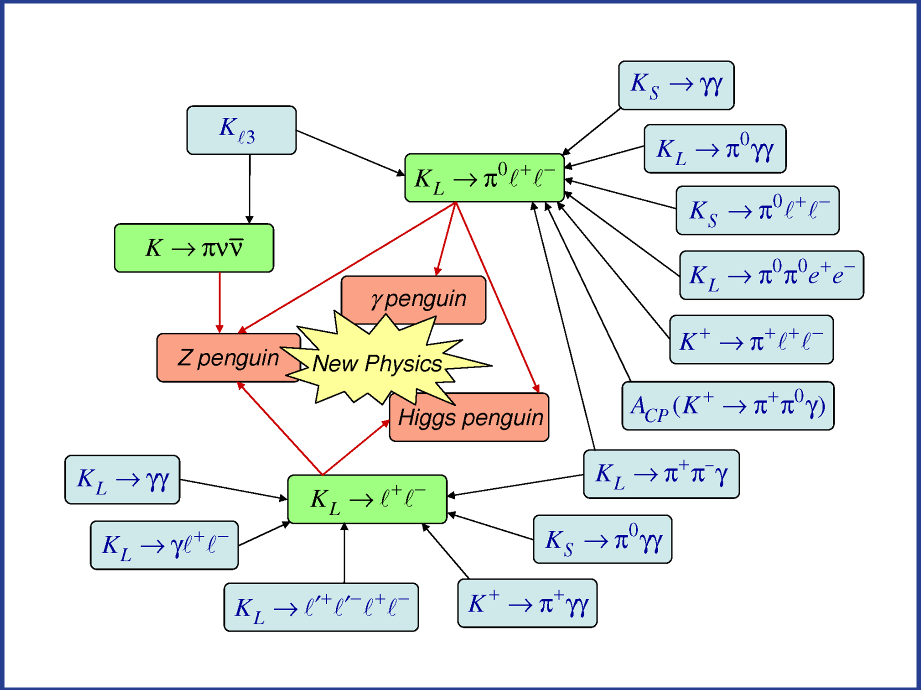
- Statistics will be vital
- Time Structure and flexibility will be essential:

| Physics | Problem | PX Solution |
|---|---|---|
| Mu2e: Vary Z | Muon Lifetime in muonic atom shortens with *Z* | Flexible time structure |
| Want more channels: $\mu^+ \rightarrow e\gamma$ , $\mu^+ \rightarrow e^+e^+e^-$ and perhaps others | Stopped Muon Experiments require low instantaneous intensity, unlike Mu2e which is a captured muon experiment | Flexible time structure |
| *and running all of these in a unified program needs flux* | | |

# Technology of Upgraded Mu2e

- Aligned with Neutrino Factories and Muon Colliders:
  - Capture Solenoids with High Fields
    - How Do You Build Them: layers, winding, splices, heating, etc?
    - Radiation Damage to Superconductors?
  - Manipulation of Phase Space of Muon Beams
    - Momentum spread, time spread
- Similar Problems in Mu2e, and recognized in community:
  - At NuFact 2012: three Mu2e technology talks on above questions, well-attended, *lots* of questions

# Future: $g_\mu$-2, Kaons and Rare Decays




C. Smith, NA62 Physics Handbook, 12/9/2009

# $g_\mu$-2 Evolution

- First see what this decade's experiment says
  - Results by ~ 2017
- Continue to improve theory errors (lattice HLBL)
- Project X:
  - Negative Muons
    - Lower emittance muon beams, lessening systematics
    - Measure $g_\mu$-2 as a systematic check of $\mu^+$ result
    - Enables checks of CPT
  - New Techniques?
    - Frozen spin, ultra-cold beams
  - $g_\mu$-2 is a incisive probe: reduce errors, keep pushing limits

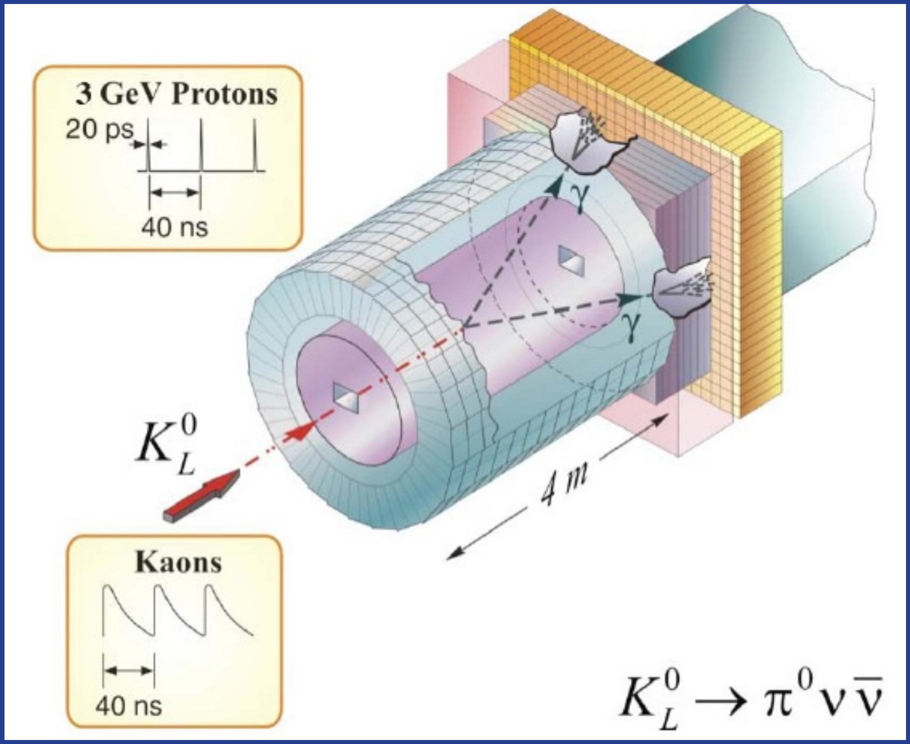
# Precision Measurement of $K_L^0 \to \pi^0 \nu \bar{\nu}$

$$B\left(K_L^0 \to \pi^0 \nu \bar{\nu}\right) \approx 2.8 \times 10^{-11}$$

- Nothing in, nothing out…
  - Two particles invisible, need positive ID of $\pi^\circ$
- $\pi^\circ$ backgrounds ~ $10^9$ larger
  - principal problem: $K_L^0 \to \pi^0 \pi^0$
- Veto, Neutrons (typically neutron beam with kaon contamination), hermeticity,…
- Need a *measurement* of the background

# Project X: $K_L^0 \to \pi^0 \nu \bar{\nu}$ Experimental Concept

- Use TOF to work in $K_L^0$ center-of-mass
- Identify and eliminate background $K_L^0 \to \pi^0 \pi^0$
- Reconstruct $\pi^0 \to \gamma\gamma$ with high-efficiency pointing calorimeter
- *4π* photon and charged particle veto

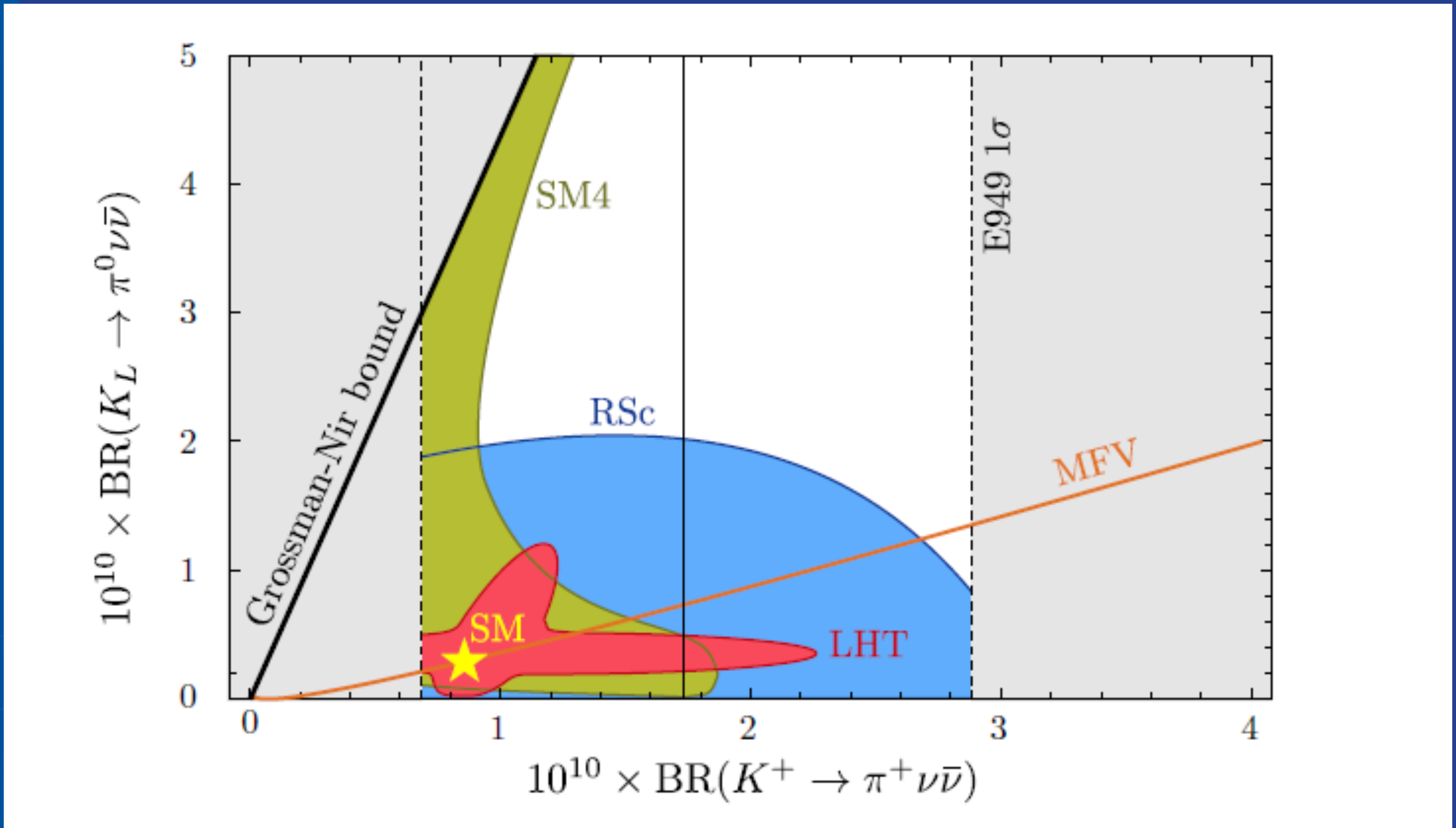



Need PX for time structure, 3 GeV for production

# Constraining BSM physics

Grossman-Nir: Im(ℜ)<|ℜ| + lifetime + isospin
MFV: no new CP beyond CKM phase yields a straight line
LHT: Littlest Higgs with T-Parity
RSc: Randall-Sundrum with ``custodial protection"
SM4: 4th Generation

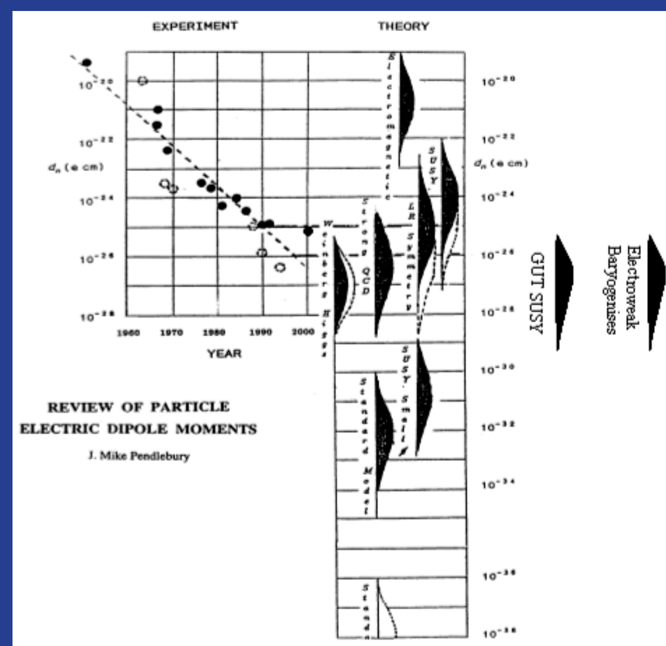
$$B(K_L^0 \to \pi^0 \nu\bar{\nu}) \text{ vs. } B(K^+ \to \pi^+ \nu\bar{\nu})$$




D. M. Straub, arXiv:1012.3893 [hep-ph].

# Electric Dipole Moments at Project X

**“n-EDM has killed more theories than any other single experiment”**




# Why EDMs?

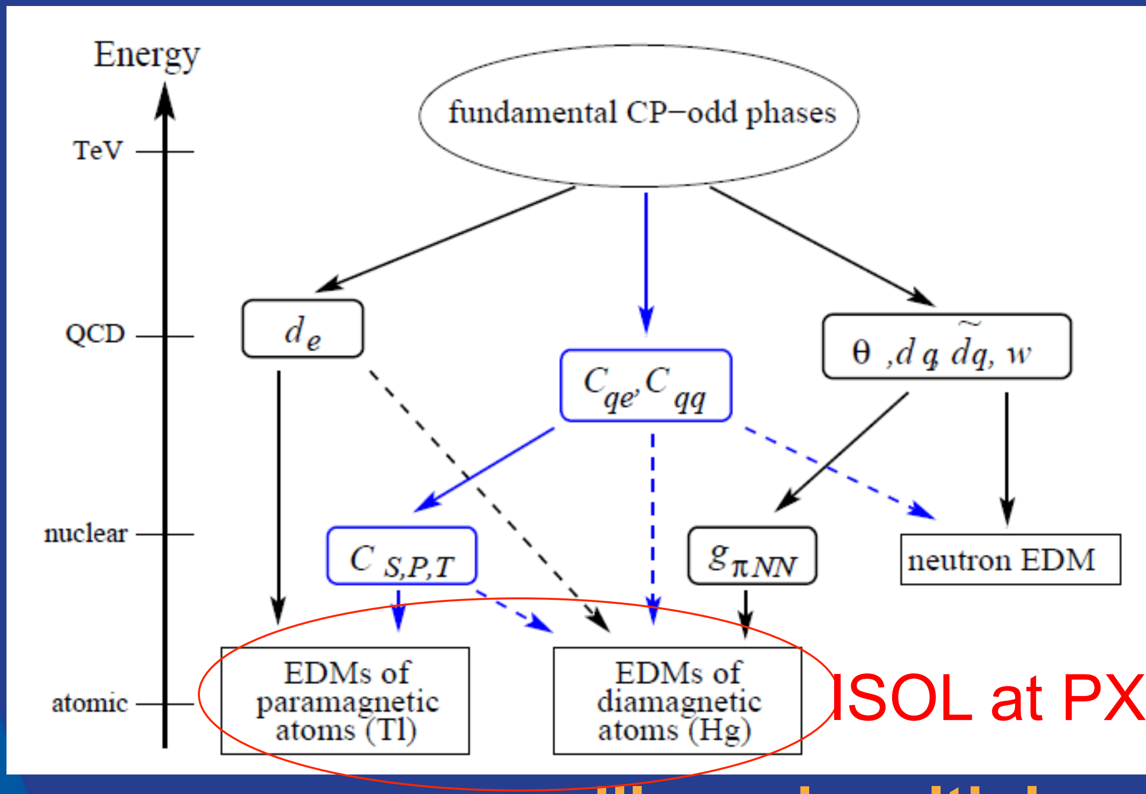
- **CP Violation and the Matter/Antimatter Asymmetry in the Universe**
  - Sakharov Criteria
    - Baryon Number Violation
    - CP & C violation
    - Departure from Thermal Equilibrium
  - Standard Model CP violation is insufficient
    - Must search for new sources of CP
      - B-factories, LHC, Neutrinos, EDMs
  - Electroweak Baryogenesis still viable

M. Carena, M. Quiros, A. Riotto, I. Vilja and C. E. Wagner, Nucl. Phys. B 503, 387 (1997)

Li, Profumo, Ramsey-Musolf : arXiv:0811.1987

Cirigliano, Li, Profumo, Ramsey-Musolf: JHEP 1001:002,2010

# Origin of elementary EDMs




**we will need multiple systems to identify the origin of new CP violation**

Electric dipole moments as probes of new physics
Maxim Pospelov, Adam Ritz
Annals Phys.318:119-169,2005

# EDMs at Project X

- What experiments are possible? (from PX workshop)
  - Proton EDM in storage ring
    - Uses infrastructure, expertise & high currents at Fermilab
  - Radioactive atom EDM
    - Isotope Separator On-Line (ISOL) production facility
  - Neutron EDM
    - High densities of Ultra-Cold Neutrons via spallation
- A new set of experiments for FNAL enabled by Project X
  - Still baryogenesis and leptogenesis, but different methods
  - Adds strong CP problem to experimental program

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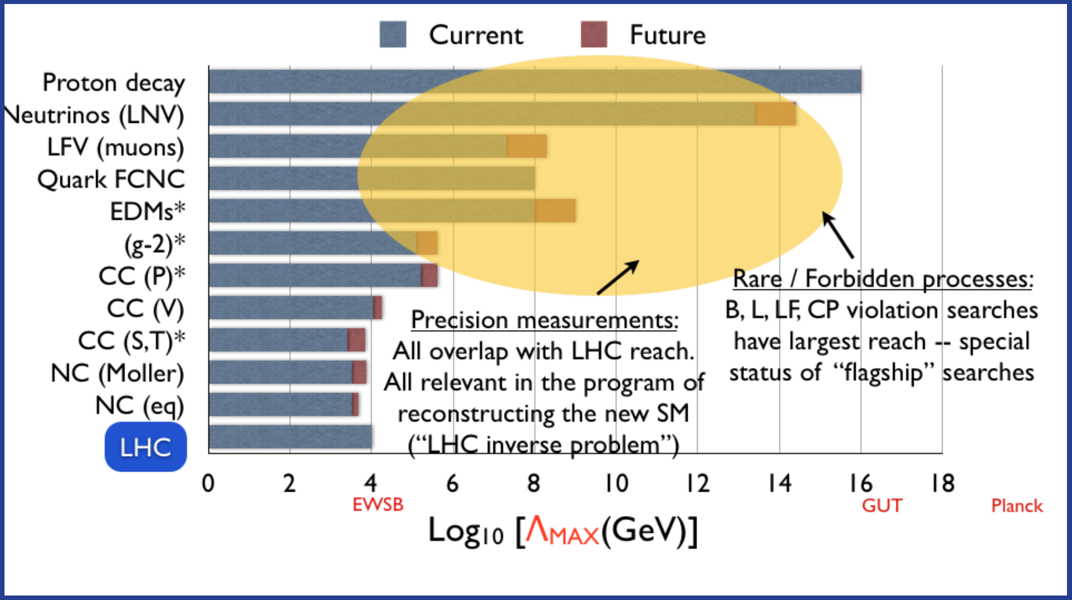
# Summary: Discovery and Discrimination in an Evolving Program



# Summary: Discovery and Discrimination at an evolving Laboratory

- *Discovery*:
  - Mu2e can discover cLFV from SUSY processes and much more because of our mass reach
  - $g_\mu$-2 has enormous, complementary capabilities
  - Kaon system:
    - new surprises or further constrains or both
- *Discrimination*:
  - LHC barely started, and may find surprises–and SUSY is far from ruled out. The discriminating power of cLFV, $g_\mu$-2, and kaons is enormous.
- *Evolution of FNAL*
  - Muon Campus at Booster → Staged Project X enabling this physics

# Near-term FNAL Intensity Frontier Program

- $g_\mu$-2 in next few years, followed by Mu2e at end of decade, are world-class experiments
  - Addressing fundamental questions with huge discovery potential
- Muon Campus and especially $g_\mu$-2 are re-using FNAL/DOE investment and infrastructure
  - Adaptions of antiproton complex for two experiments with potential for expansion
  - Re-using $g_\mu$-2 ring from BNL
- SeaQuest continues studies of QCD

- And ORKA may provide incisive measurements of CP-violating amplitudes

# Long-term possibilities

- Project X can build on this program
  - Muon Campus: Mu2e upgrades and a broad cLFV program
  - Kaon program : another potential view into BSM physics
  - EDMs can expand FNAL's horizon
    - partnership with nuclear fundamental symmetry community

# Intensity Frontier Program Summary

- Important experiments with huge impact
  - World-class physics starting with $g_\mu$-2 and Mu2e leading to world-leading programs at Project X
- Feasible: based on experience and known techniques
  - $g_\mu$-2 and SeaQuest
  - Lab has put significant technical and computing resources into Mu2e simulations (and is building a new cross-experiment framework for IF computing)
- Staff Leadership (on these four experiments):
  - Two Co-Spokespersons, Two Project Managers, One Early Career Award
- Lab Planning is Strategic and Optimized
  - Muon Campus and recycling of infrastructure
  - Staged Plan to Project X

# Broad, coherent program studying fundamental questions

The program is staged from the next few years and the Muon Campus through Stages of Project X.  It builds on FNAL's expertise and core strengths

- Each stage has compelling physics and stands on its own
- Each stage leads to the next
- Intensity Frontier Program addresses the most basic questions in our field with a steady and flexible plan